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Dated 27 May 2004

GB 0311739.7

By virtue of a direction given under Section 30 of the Patents Act 1977, the application is proceeding in the name of

QUINTEL TECHNOLOGY LIMITED,
18 Upper Grosvenor Street,
LONDON,
W1K 7PW,
United Kingdom

Incorporated in the United Kingdom,

[ADP No. 08697401001]

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22MAY03 E809286-1 D02776
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Request for grant of a patent

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1.	Your reference.	IP/P7243/1
2.	Patent application number *(The Patent Office will fill in this part)*	0311739.7
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	QINETIQ LIMITED Registered Office 85 Buckingham Gate London SW1E 6PD United Kingdom
	Patents ADP number *(if you know it)*	8183873010.
	If the applicant is a corporate body, give the country/state of its incorporation	GB
4.	Title of the invention	PHASED ARRAY ANTENNA SYSTEM WITH ADJUSTABLE ELECTRICAL TILT
5.	Name of your agent *(if you have one)*	Williams Arthur Wyn Spencer
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	QINETIQ LIMITED IP Formalities A4 Bldg Cody Technology Park Ively Road Farnborough Hants GU14 0LX United Kingdom
	Patents ADP number *(if you know it)*	8242497001

SECTION 30 (1977 ACT) APPLICATION FILED 11/8/03

		Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	UNITED KINGDOM	0311371.9	17 MAY 2003

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11. I / We request the grant of a patent on the basis of this application.

Signature A R W Williams Date 21 MAY 2003

DR A W S WILLIAMS

12. Name and daytime telephone number of person to contact in the United Kingdom Mrs Linda Bruckshaw 01252 392722

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DUPLICATE

Phased Array Antenna System with Adjustable Electrical Tilt

The present invention relates to a phased array antenna system with adjustable electrical tilt. It is suitable for use in many areas of telecommunications but finds particular application in cellular mobile radio networks, commonly referred to as mobile telephone networks. More specifically, but without limitation, the antenna system of the invention may be used with second generation (2G) mobile telephone networks such as the GSM system, and third generation (3G) mobile telephone networks such as the Universal Mobile Telephone System (UMTS).

Operators of cellular mobile radio networks generally employ their own base-stations, each of which has at least one antenna. In a cellular mobile radio network, the antennas are a primary factor in defining a coverage area in which communication to the base station can take place. The coverage area is generally divided into a number of overlapping cells, each associated with a respective antenna and base station.

The antenna of each sector is connected to a base station for radio communication with all of the mobile radios in that cell. Base stations are interconnected by other means of communication, usually point-to-point radio links or fixed land-lines, allowing mobile radios throughout the cell coverage area to communicate with each other as well as with the public telephone network outside the cellular mobile radio network.

Cellular mobile radio networks which use phased array antennas are known: such an antenna comprises an array (usually eight or more) individual antenna elements such as dipoles or patches. The antenna has a radiation pattern consisting of a main lobe and sidelobes. The centre of the main lobe is the antenna's direction of maximum sensitivity, i.e. the direction of its main radiation beam. It is a well known property of a phased array antenna that if signals received by antenna elements are delayed by a delay which varies linearly with distance from an edge of the array, then the antenna main radiation beam is steered towards the direction of increasing delay. The angle between main radiation beam centres corresponding to zero and non-zero variation in delay, i.e. the angle of steer, depends on the rate of change of delay with distance across the array.

Delay may be implemented equivalently by changing signal phase, hence the expression phased array. The main beam of the antenna pattern can therefore be

altered by adjusting the phase relationship between signals fed to different antenna elements. This allows the beam to be steered to modify the coverage area of the antenna.

Operators of phased array antennas in cellular mobile radio networks have a requirement to adjust their antennas' vertical radiation pattern, i.e. the pattern's cross-section in the vertical plane. This is necessary to alter the vertical angle of the antenna's main beam, also known as the "tilt", in order to adjust the coverage area of the antenna. Such adjustment may be required, for example, to compensate for change in cellular network structure or number of base stations or antennas. Adjustment of antenna angle of tilt is known both mechanically and electrically, and both individually or in combination.

Antenna angle of tilt may be adjusted mechanically by moving antenna elements or their housing (radome): it is referred to as adjusting the angle of "mechanical tilt". As described earlier, antenna angle of tilt may be adjusted electrically by changing time delay or phase of signals fed to or received from each antenna array element (or group of elements) without physical movement: this is referred to as adjusting the angle of "electrical tilt".

When used in a cellular mobile radio network, a phased array antenna's vertical radiation pattern (VRP) has a number of significant requirements:

1. high main lobe (or boresight) gain;
2. a first upper side lobe level sufficiently low to avoid interference to mobiles using a base station in a different network;
3. a first lower side lobe level sufficiently high to allow communications in the immediate vicinity of the antenna.

The requirements are mutually conflicting, for example, increasing the boresight gain will increase the level of the side lobes. A first upper side lobe level, relative to the boresight level, of -18dB has been found to provide a convenient compromise in overall system performance.

The effect of adjusting either the angle of mechanical tilt or the angle of electrical tilt is to reposition the boresight so that it points either above or below the horizontal plane, and hence changes the coverage area of the antenna.

It is desirable to be able to vary both the mechanical tilt and the electrical tilt of a cellular radio base station's antenna: this allows maximum flexibility in optimisation of cell coverage, since these forms of tilt have different effects on antenna ground coverage and also on other antennas in the station's immediate vicinity. Moreover, operational efficiency is improved if the angle of electrical tilt can be adjusted remotely from the antenna assembly. Whereas an antenna's angle of mechanical tilt may be adjusted by re-positioning its radome, changing its angle of electrical tilt requires additional electronic circuitry which increases antenna cost and complexity. Furthermore, if a single antenna is shared between a number of operators it is preferable to provide an individual angle of electrical tilt for each operator.

The need for an individual angle of electrical tilt from a shared antenna has hitherto resulted in compromises in the performance of the antenna. The boresight gain will decrease in proportion to the cosine of the angle of tilt due to a reduction in the effective aperture of the antenna. Further reductions in boresight gain may result as a consequence of the method used to change the angle of tilt.

R. C. Johnson, Antenna Engineers Handbook, 3rd Ed 1993, McGraw Hill, ISBN 0 - 07 - 032381 - X, Ch '20, Figure 20-2 discloses a known method for locally or remotely adjusting a phased array antenna's angle of electrical tilt. In this method a radio frequency (RF) transmitter carrier signal is fed to the antenna and distributed to the antenna's radiating elements. Each antenna element has a variable phase shifter associated with it so that signal phase can be adjusted as a function of distance across the antenna to vary the antenna's angle of electrical tilt. The distribution of power when not tilted is proportioned so as to set the side lobe level and boresight gain. Optimum control of the angle of tilt is obtained when the phase front is controlled for all angles of tilt so that the side lobe level is not increased over the tilt range. The angle of electrical tilt can be adjusted remotely, if required, by using a servo-mechanism to control the position of the phase shifters.

This prior art method antenna has a number of disadvantages. A variable phase shifter is required for every antenna element. The cost of the antenna is high due to the

number of such phase shifters required. Cost may be reduced by using a single common delay device or phase shifter for a group of elements instead of per element, but this increases the side lobe level. Mechanical coupling of delay devices is used to adjust delays, but it is difficult to do this correctly; moreover, mechanical links and gears result in non-optimum distribution of delays. The upper side lobe level increases when the antenna is tilted downwards thus causing a potential source of interference to mobiles using other base stations. If the antenna is shared by a number of operators, the operators then have a common angle of electrical tilt instead of different angles. Finally, if the antenna is used in a communications system having up-link and down-link at different frequencies (frequency division duplex system), the angle of electrical tilt in transmit is different to that in receive.

International Patent Application Nos. PCT/GB2002/004166 and PCT/GB2002/004930 describe locally or remotely adjusting an antenna's angle of electrical tilt by means of a difference in phase between a pair of signal feeds connected to the antenna.

It is an object of the present invention to provide an alternative form of phased array antenna system.

The present invention provides a phased array antenna system with adjustable electrical tilt and comprising an array of antenna elements characterised in that the system incorporates:

a) a variable phase shifter for introducing a variable relative phase shift between first and second RF signals,
b) splitting apparatus for dividing the relatively phase shifted first and second signals into component signals, and
c) a signal combining and phase shifting network for vectorially combining and relatively phase shifting the component signals to provide drive signals with appropriate relative phasing for the antenna elements.

The invention provides the advantage that it is possible to implement adjustable electrical tilt without providing a respective variable phase shifter for each of the antenna elements in the array.

The antenna system may have an odd number of antenna elements comprising a central antenna element separated from adjacent antenna elements by a distance which

is half that between other adjacent antenna element pairs. The variable phase shifter may be a first variable phase shifter, the system including a second variable phase shifter arranged to phase shift a component signal which has been phase shifted by the first variable phase shifter, and the second variable phase shifter providing a further component signal output for the signal combining and phase shifting network either directly or via one or more splitter/variable phase shifter combinations.

The variable phase shifter may be one of a plurality of variable phase shifters, the signal phase shifting and combining network being arranged to produce antenna element drive signals from component signals some of which have passed through all the variable phase shifters and some of which have not.

The splitting apparatus may be arranged to divide a component signal into further component signals for input to the signal phase shifting and combining network. The signal phase shifting and combining network may employ phase shifters and hybrid couplers for phase shifting and vectorially combining the component signals. The hybrid couplers may be 180 degree hybrid couplers. They may be designed to convert input signals A and B into vector sums other than (A+B) and (A-B). Each phase shifter may be implemented by a splitter and a 180 degree hybrid coupler having a sum output for providing a phase shifted signal and a difference output terminated with a matched load.

Each phase shifter may be implemented by a splitter and a 180 degree hybrid coupler having a sum output for providing a phase shifted signal and a difference output terminated with a matched load.

The splitting apparatus, variable phase shifter, and the signal phase shifting and combining network may be co-located with the antenna array to form an antenna assembly, the assembly having a single RF input power feeder from a remote source. The splitting apparatus may incorporate first, second and third splitters, the first splitter being located with the variable phase shifter remotely from the second and third splitters, the second and third splitters, the signal phase shifting and combining network and the antenna array being co-located as an antenna assembly, and the assembly having dual RF input power feeders from a remote source at which the first splitter and variable phase shifter are located.

The variable phase shifter may be a first variable phase shifter connected in a transmit channel, the system including a second variable phase shifter connected in a receive channel and the signal phase shifting and combining network being arranged to operate in both transmission and reception modes by producing antenna element drive signals in response to a signal in the transmit channel and producing a receive channel signal from signals developed by antenna elements operating in reception mode.

The variable phase shifter may be one of a plurality of variable phase shifters associated with respective operators, and the system includes filtering and combining apparatus for routing signals on to common signal feed apparatus after phase shifting in respective variable phase shifters, the common signal feed apparatus being connected to splitting apparatus and a signal combining and phase shifting network for providing signals to the antenna containing contributions from both operators with independently adjustable electrical tilt. The plurality of variable phase shifters may comprise a respective pair of variable phase shifters associated with each operator, and the system may have components which have both forward and reverse signal processing capabilities such that the system is operative in transmit and receive modes with independently adjustable electrical tilt in both modes.

In another aspect, the present invention provides a method of providing a phased array antenna system with adjustable electrical tilt, the system including an array of antenna elements, characterised in that the method incorporates:

a) introducing a variable relative phase shift between first and second RF signals,
b) dividing the relatively phase shifted first and second signals into component signals, and
c) vectorially combining and relatively phase shifting the component signals to provide drive signals with appropriate relative phasing for the antenna elements.

The array may have an odd number of antenna elements comprising a central antenna element separated from adjacent antenna elements by a distance which is half that between other adjacent antenna element pairs.

The method may include generating at least one component signal which has undergone phase shifting in a plurality of variable phase shifters. The variable phase shifters may be ganged, the method including producing antenna element drive signals

from component signals some of which have passed through all the variable phase shifters and some of which have not.

The method may include dividing a component signal into further component signals for input to the signal phase shifting and combining network. It may employ phase shifters and hybrid couplers for phase shifting and vectorially combining the component signals. The hybrid couplers may be 180 degree hybrid couplers. They may be designed to convert input signals A and B into vector sums other than (A+B) and (A-B). Each phase shifter may be implemented by a splitter and a 180 degree hybrid coupler having a sum output for providing a phase shifted signal and a difference output terminated with a matched load.

The method may include feeding a single RF input signal from a remote source for splitting, variable phase shifting and vectorial combining in a network co-located with the antenna array to form an antenna assembly. It may alternatively include feeding two RF input signals with variable phase relative to one another from a remote source to an antenna assembly and splitting, phase shifting and combining signals in a network co-located with the antenna array. It may employ a transmit channel and a receive channel for operation in both transmission and reception modes, producing antenna element drive signals in response to a signal in the transmit channel and producing a receive channel signal from signals developed by antenna elements operating in reception mode.

The variable phase shifter may be one of a plurality of variable phase shifters associated with respective operators, and the method may include:

a) filtering and combining signals on to common signal feed apparatus after phase shifting in respective variable phase shifters, the common signal feed apparatus being connected to the splitting apparatus and the signal combining and phase shifting network;

b) providing signals to the antenna containing contributions from both operators; and

c) independently adjusting electrical tilt associated with each operator.

The plurality of variable phase shifters may comprise a respective pair of variable phase shifters associated with each operator, the method may employ components which have both forward and reverse signal processing capabilities, and the method may include

operating in transmit and receive modes with independently adjustable electrical tilt in both modes.

In order that the invention might be more fully understood, embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings, in which:-

Figure 1 shows a phased array antenna's vertical radiation pattern (VRP) with zero and non-zero angles of electrical tilt;

Figure 2 illustrates a prior art phased array antenna having an adjustable angle of electrical tilt;

Figure 3 is a block diagram of a phased array antenna system of the invention;

Figure 4 shows in more detail a signal combining network used in the Figure 3 system;

Figure 5 is a phase diagram of antenna element signals corresponding to a ninety degree phase shift introduced by a variable phase shifter in the Figure 3 system;

Figures 6 and 7 are block diagrams of parts of further phased array antenna systems of the invention incorporating eleven and twelve antenna elements respectively (element spacing is not wholly to scale in Figure 6);

Figure 8 is a phase diagram of antenna element signals corresponding to a ninety degree phase shift introduced by a variable phase shifter in the Figure 7 system;

Figure 9 illustrates implementation of a fixed 180 degree phase shift or delay using a splitter and a 180 degree hybrid coupler;

Figure 10 is a block diagram of part of another phased array antenna system of the invention employing two variable phase shifters;

Figure 11 is a block diagram of part of an antenna system of the invention similar to that shown in Figure 10 but employing ganged variable phase shifters;

Figures 12 and 13 illustrate use of the invention with single and dual feeders respectively;

Figure 14 shows a modification to the invention allowing angles of electrical tilt in transmit mode and receive mode to be independently adjustable;

Figure 15 is a block diagram of another phased array antenna system of the invention illustrating antenna sharing by multiple users with dual feeds and joint transmit/receive capability; and

Figure 16 is a variant of the antenna system of Figure 10 with variable phase shifters located remotely from one another.

Referring to Figure 1, there are shown vertical radiation patterns (VRP) 10a and 10b of an antenna 12 which is a phased array of individual antenna elements (not shown). The antenna 12 is planar, has a centre 14 and extends perpendicular to the plane of the drawing. The VRPs 10a and 10b correspond respectively to zero and non-zero variation in delay or phase of antenna element signals with distance across the antenna 12. They have respective main lobes 16a, 16b with centre lines or "boresights" 18a, 18b, first upper sidelobes 20a, 20b and first lower sidelobes 22a, 22b; 18c indicates the boresight direction for zero variation in delay for comparison with the non-zero equivalent 18b. When referred to without the suffix a or b, e.g. sidelobe 20, either of the relevant pair of elements is being referred to without distinction. The VRP 10b is tilted (downwards as illustrated) relative to VRP 10a, i.e. there is an angle - the angle of tilt - between main beam centre lines 18b and 18c which has a magnitude dependent on the rate at which delay varies with distance across the antenna 12.

The VRP has to satisfy a number of criteria: a) high boresight gain; b) the first upper side lobe 20 should be at a level low enough to avoid causing interference to mobiles using another base station; and c) the first lower side lobe 22 should be sufficient for communications to be possible in the antenna's immediately vicinity.

The requirements are mutually conflicting: for example, maximising boresight gain increases side lobes 20, 22. Relative to a boresight level (length of main beam 16), a first upper side lobe level of -18dB has been found to provide a convenient compromise in overall system performance. Boresight gain decreases in proportion to the cosine of

the angle of tilt due to reduction in the antenna's effective aperture of the. Further reductions in boresight gain may result depending on how the angle of tilt is changed.

The effect of adjusting either the angle of mechanical tilt or the angle of electrical tilt is to reposition the boresight so that it points either above or below the horizontal plane, and hence increases or decreases the coverage area of the antenna. For maximum flexibility of use, a cellular radio base station preferably has available both mechanical tilt and electrical tilt since each has a different effect on ground coverage and also on other antennas in the immediate vicinity. It is also convenient if an antenna's electrical tilt can be adjusted remotely from the antenna. Furthermore, if a single antenna is shared between a number of operators it is preferable to provide an individual angle of electrical tilt for each operator.

Referring now to Figure 2, a prior art phased array antenna system 30 is shown in which the angle of electrical tilt is adjustable. The system 30 incorporates an input 32 for a radio frequency (RF) transmitter carrier signal, the input being connected to a power distribution network 34. The network 34 is connected via phase shifters Phi.E0, Phi.E1L to Phi.E[n]L and Phi.E1U to Phi.E[n]U to respective radiating antenna elements E0, E1L to E[n]L and E1U to E[n]U respectively of the phased array antenna system 30: here suffixes U and L indicate upper and lower respectively, n is an arbitrary positive integer greater than 2 and defining phased array size, and dotted lines such as 36 indicating the relevant element may be replicated as required for any desired array size.

The phased array antenna system 30 operates as follows. An RF transmitter carrier signal is fed via the input 32 to the power distribution network 34: the network 34 divides this signal (not necessarily equally) between the phase shifters Phi.E0, Phi.E1L to Phi.E[n]L and Phi.E1U to Phi.E[n]U, which phase shift the signals they receive and pass on the resulting phase shifted signals to respective associated antenna elements E0, E1L to E[n]L, E1U to E[n]U. The phase shifts and signal amplitudes to each element are chosen to select an appropriate angle of electrical tilt. The distribution of power by the network 34 when the angle of tilt is zero is chosen to set the side lobe level and boresight gain appropriately. Optimum control of the angle of tilt is obtained when the phase front is controlled for all angles of tilt so that the side lobe level is not increased significantly over the tilt range. The angle of electrical tilt can be adjusted remotely, if required, by using a servo-mechanism to control the phase shifters Phi.E0, Phi.E1L to Phi.E[n]L and Phi.E1U to Phi.E[n]U, which may be mechanically actuated.

The phased array antenna system 30 has a number of disadvantages as follows:

a) a respective phase shifter is required for each antenna element, or per group of elements;

b) the cost of the antenna is high due to the number of phase shifters required;

c) cost reduction by applying phase shifters to groups of elements increases the side lobe level;

d) mechanical coupling of the phase shifters to set delays correctly is difficult and mechanical links and gears are used which result in a non-optimum delay scheme;

e) the upper side lobe level increases when the antenna is tilted downwards causing a potential source of interference to mobiles using other base stations;

f) if an antenna is shared by different operators, all must use the same angle of electrical tilt;

g) in a system with up-link and down-link at different frequencies (frequency division duplex system), the angle of electrical tilt in transmit is different from that in receive;

Referring now to Figure 3, a phased array antenna system 40 of the invention is shown which has an adjustable angle of electrical tilt. The system 40 incorporates five functional regions 40_1 to 40_5 referred to in the art as "levels" and indicated between pairs of dotted lines such as 41. It has an input 42 for an RF carrier transmission signal: the input 42 is connected as input to a power splitter 44 providing two output signals V1a, V1b, these becoming input signals to a variable phase shifter 46 and a first fixed phase shifter 48 respectively. The phase shifters 46 and 48 may equivalently be considered as time delays. They provide respective output signals V2b and V2a to two power splitters 52 and 54 respectively. The power splitters 52 and 54 have n outputs such as 52a and 54a respectively: here n is a positive integer equal to 2 or more, and dotted outputs 52b and 54b indicate the output in each case may be replicated as required for any desired phased array size.

The power splitter outputs such as 52a and 54a provide output signals Va1 to Va[n] and Vb1 to Vb[n] respectively (illustrated without the V symbol). As will be described later in more detail, some of these output signals may be equal to others and some unequal. In one embodiment (to be described) having ten antenna elements (n = 5),

Va1 = Va2 = Va3, Vb3 = Vb4 = Vb5; Va4 = Vb2 and Va5 = Vb1. These output signals are fed to the phase shifting and combining level 40_4, which contains second and third fixed phase shifters 56 and 58 and vector combining networks indicated collectively by 60. The level 40_4 will be described in more detail later: it provides drive signals to equispaced antenna elements 62_1 to 62_n of a phased array 62 via respective fixed phase shifters 64_1 to 64_n. Here as before n is an arbitrary positive integer equal to or greater than 2 but equal to the value of n for the power splitters 52 and 54, and phased array size is 2n antenna elements. Inner antenna elements 62_2 and 62_3 are shown dotted to indicate they may be replicated as required for any desired phased array size.

The phased array antenna system 40 operates as follows. An RF transmitter carrier signal is fed (single feeder) via the input 42 to the power splitter 44 where it is divided into signals V1a and V1b of equal power. The signals V1a and V1b are fed to the variable and fixed phase shifters 46 and 48 respectively. The variable phase shifter 46 applies an operator-selectable phase shift or time delay, and the degree of phase shift applied here controls the angle of electrical tilt of the phased array 62 of antenna elements 62_1 etc. The fixed phase shifter 48 is not essential but convenient: it applies a fixed phase shift which for convenience is chosen to be half the maximum phase shift ϕ_M applicable by the variable phase shifter 46. This allows V1a to be variable in phase in the range $-\phi_M/2$ to $+\phi_M/2$ relative to V1b, and these signals after phase shift become V2b and V2a as has been said after output from the phase shifters 46 and 48.

Each of the power splitters 52 and 54 divides signals V2b or V2a into a respective set of n output signals Vb1 to Vb[n] or Va1 to Va[n], where the power of each signal in each set Vb1 etc or Va1 etc is not necessarily equal to the powers of the other signals in its set. The variation of signal powers across the sets Va1 etc and Vb1 etc is different for different numbers of antenna elements 62_1 etc in the array 62.

One of the set of output signals Vb1 to Vb[n] is fed to a respective fixed antenna phase shifter 64_3 via the second phase shifter 56, and one of the set of output signals Va1 to Va[n] is likewise fed to another antenna phase shifter 64_8 via the third phase shifter 58. The second and third phase shifters 56 and 58 introduce -180 degree phase shifts like the combining networks 60. Other signals in the sets Vb1 to Vb[n] and Va1 to Va[n] are combined in pairs in the networks 60 to produce vectorially added resultant signals for driving respective antenna elements 62_1 *etc* via phase shifters 64_1 *etc.* The fixed phase

shifters 64_1 *etc.* impose fixed phase shifts which vary between different antenna elements 62_1 *etc.* according to element geometrical position across the array 62: this sets a zero reference direction (18a or 18b in Figure 1) for the array 62 boresight when zero phase difference between the signals V1a and V1b imposed by the variable phase shifter 46. The antenna phase shifters 64_1 *etc.* are not essential, but they are preferred because they can be used to a) proportion correctly the phase shift introduced by the tilt process, b) optimise suppression of the side lobes over the tilt range, and c) introduce an optional fixed angle of electrical tilt.

The angle of electrical tilt of the array 60 is variable simply by using one variable phase shifter, the variable phase shifter 46. This compares with the prior art requirement to have multiple variable phase shifters, one for every antenna element or sub-group of antenna elements. When the phase difference introduce by the variable phase shifter 46 is positive relative to the fixed phase shift 48 the antenna tilts in one direction, and when that phase difference is negative the antenna tilts in the opposite direction.

If there are a number of users, each user may have a respective phased array antenna system 40. Alternatively, if it is required that users employ a common antenna 62, then each user may have a respective set of levels 40_3, 40_4 and 40_5 in Figure 3, and a combining network is required to combine signals from the resulting plurality of sets of phase shifters 64_1 *etc.* for feeding to the antenna array 62. Published International Patent Application No. WO 02/082581 A2 describes such a network.

It can be shown that the antenna system 40 has good side lobe suppression that is maintained over its electrical tilt range. The antenna system 40 can be implemented at lower cost than contemporary designs offering a similar level of performance. Its electrical tilt may be adjusted remotely using a single variable delay device, and this permits different operators to share it while providing each operator with an individual angle of electrical tilt. The angle of electrical tilt in transmit may either be the same, or different from that in receive by modifying the antenna system 40 to include different paths and phase shifters for transmit and receive as will be described later.

Referring now to Figure 4, there is shown part of an implementation 70 of the invention for a phased array 62 of ten elements 62_1 to 62_{10}. Parts equivalent to those previously described are like referenced. Figure 4 corresponds to parts 40_3 to 40_5 of Figure 3, and splitters 52 and 54 are shown exchanged in position. As in Figure 3, the splitters 52 and

54 receive respectively input signals V2b and V2a of equal power but variable relative phase. They each split their respective inputs into five signals, three of which are of the same power (a or b), and the other two are 0.32 and 0.73 of that power (0.32 or 0.73 of a or b).

Eight of the ten signals from the splitters 52 and 54 pass to four vector combining devices 60_1 to 60_4: each of these devices is a 180 degree hybrid directional coupler having two input terminals designated A and B and two output terminals designated A+B and A-B. As indicated by the terminal designations, on receipt of input signals at A and B, each of the couplers 60_1 to 60_4 produces two output signals which are the vector sum and difference of the input signals respectively. Table 1 below shows the input signal amplitudes received by the couplers 60_1 to 60_4 and the output signals in vector form generated in response, expressed in terms of arbitrary values a and b in each case.

Table 1

Coupler	A Input	B Input	A + B Output	A - B Output
60_1	a	0.73b	a + 0.73b	a - 0.73b
60_2	a	0.32b	a + 0.32b	a - 0.32b
60_3	b	0.32a	b + 0.32a	b - 0.32a
60_4	b	0.73a	b + 0.73a	b - 0.73a

Table 2 below shows the antenna elements which receive the output signals generated by the splitters 52 and 54 and couplers 60_1 to 60_4 via antenna phase shifters (PS) 64_1 to 64_{10}. In this connection it is to be noted that one signal a or b from each splitter 52 or 54 is not routed to antenna phase shifter 64_3 or 64_8 via a coupler but instead via a -180 degree phase shifter 56 or 58. The phase shifter pairs $56/64_3$ and $58/64_8$ are fixed and each could be implemented as a single phase shift, but they are shown separately to illustrate mode of operation more clearly.

Table 2

Antenna Element	Signal Power		Antenna Element	Signal Power
62_1	a - 0.73b		62_6	b + 0.73a
62_2	a - 0.32b		62_7	b + 0.32a
62_3	a		62_8	b
62_4	a + 0.32b		62_9	b - 0.32a
62_5	a + 0.73b		62_{10}	b - 0.73a

The input splitter 44 in Figure 3 may (optionally) provide unequal power splitting so that the voltages V2a and V2b are different in Figures 3 and 4. Furthermore, the couplers 60_1 to 60_4 that (as described) provide sum and difference vectors A+B and A-B may (optionally) subsume all or part of the function of splitters 52 and 54: i.e. they may instead be designed to convert inputs A and B into vector sums other than (A+B) and (A-B), for example a sum of xA+yB where x and y are numerical values which are not equal. This is subject to the constraint that total output power plus coupler losses must remain equal to total power input to the coupler 60_1 to 60_4. Moreover, instead of 180 degree hybrid couplers 60_1 to 60_4, hybrid couplers giving other phase shifts (e.g. 60 degrees or 120 degrees) may be used.

Referring now also to Figure 5, there is shown a vector diagram for the antenna system 70 when the phase difference between signals V2a and V2b (having the same phase as a and b respectively) is 90 degrees, which is the angle at which the phase front across the antenna elements is optimised. The antenna system 70 is optimised by determining the values of a and b in Tables 1 and 2 at 90 degree phase difference: at this value of phase difference, the antenna system 70 has a substantially linear phase front across the antenna elements at two angles of electrical tilt and an equal phase front at a mean angle of tilt. Radial arrows such as 80 terminating at 82_1 to 82_{10} indicate the magnitudes and phase angles of the phased array drive signals as they appear at the antenna elements 62_1 to 62_{10} respectively. Oblique arrows such as 84 indicate radius vector offsets (e.g. 0.73b or 0.32a) from radius vector a or b. Two arrows 84a and 84b labelled +0.73b and +0.73a are treated in the drawing as subsuming adjacent arrows 84 labelled +0.32b and +0.32a, and thereby extending back to radius vectors a and b respectively.

Bi-directional arrows such as 86 indicate phase differences between adjacent radius vectors, the phase difference being 22 degrees between signals on outermost pairs of antenna elements $62_1/62_2$ and $62_9/62_{10}$ and 18 degrees between all other pairs $62_2/62_3$ to $62_8/62_9$. The difference between 18 and 22 degrees is small in the context of a phased array: for practical purposes therefore, phase differences between adjacent pairs of antenna elements $62_i/62_{i+1}$ (1 = 1 to 9) are substantially constant and the phase variation across the array 62 is a substantially linear function of position in the array as required for normal phased array operation.

As has been said Figure 5 represents the situation for 90 degrees of phase difference between the signals a and b or V2a and V2b. A phase difference of zero corresponds to a mean angle of tilt, and positive and negative phase differences correspond to positive and negative angles of antenna tilt.

Referring now to Figure 6, there is shown part of an antenna system 100 of the invention involving an odd number of antenna elements, eleven in this example. The system 100 is equivalent to the example 70 with the addition of a small number of components, and the description which follows will concentrate on aspects of difference. Parts equivalent to those previously described are like referenced. The system 100 differs to that described earlier in that the A-B outputs of couplers 60_1 and 60_4 are not connected to phase shifters 64_1 and 64_{10} but instead to two way splitters 102 and 104 respectively. These splitters divide signals from the couplers into respective fractions c1/c2 and d1/d2: of these, c1 and d1 are fed to phase shifters 64_1 and 64_{10} for use in driving antenna elements 62_1 and 62_{10}. Fractions c2 and d2 are respectively fed to A and B inputs of an additional fifth coupler 60_5 of the same type as couplers 60_1 and 60_4. Coupler 60_5 has an A+B output which is terminated in a matched load 106, and an A-B output which is connected to an additional centrally located antenna element 62_0 via a -270 degree phase shifter 108 and an antenna phase shifter 64_0. In Figure 5, all antenna elements are equispaced by a distance S say, so the introduction of central antenna element 62_0 means that it is spaced by S/2 from neighbouring elements 62_5 and 62_6 (this is as marked in the drawing but the spacing is actually illustrated as being larger than is the case).

The net effect of the modifications in Figure 6 at the antenna array 62 is that elements 62_1 and 62_{10} have drive signals reduced to d1(b - 0.73a) and c1(a - 0.73b), and there is an extra element 62_0 with a drive signal d2(b - 0.73a) - c2(a - 0.73b).

It can be shown that the antenna system 100 has an asymmetrical Vertical Radiation Pattern when tilted downwards compared to that when tilted upwards. There is an increase in signal power fed to end antenna elements 62_1 and 62_{10} when the antenna array 62 is electrically tilted either upwards or downwards. Ideally the side lobe level would be optimally controlled when drive signal variation across the array (amplitude taper) remains substantially constant over the antenna tilt range. In order to offset consequential effects on side lobes due to increased power at end antenna elements 62_1 and 62_{10} when tilted, a number of techniques can be used as follows:

1. attenuators may be inserted in series with the end antenna elements 62_1 and 62_{10};

2. the end antenna elements 62_1 and 62_{10} may each be split into two, adding a further two elements to the antenna;

3. power may be partly diverted from the end antenna elements 62_1 and 62_{10} to elements near the centre of the antenna using further couplers; and

4. part of the power from the end antenna elements 62_1 and 62_{10} may be used to drive a centre element 62_0, as in fact is shown in Figure 6

The antenna system 100 offers the following advantages:

1. the antenna side lobe level is reduced when the antenna array 62 is electrically tilted.

2. the phase of the carrier or drive signal of the centre element 62_0 changes by 180 degrees as the electrical tilt passes through a mean value and further reduces the level of the upper side lobe when tilted downwards.

3. The effect of reducing the level of the upper side lobe when the antenna is tilted downwards is to reduce the interference caused to mobiles using channels other than that assigned to the antenna.

Referring now to Figure 7, there is shown part of an implementation 120 of the invention for a phased array 122 of twelve elements 122_1 to 122_{12}. As in Figure 3, first and second splitters 124_1 and 124_2 respectively receive input signals V2b and V2a of equal power but variable relative phase. They each split their respective inputs into three signals, i.e. signal fractions a1/a2/a3 are output from splitter 124_1 and signal fractions b1/b2/b3 from splitter 124_2, where a and b are the respective input signals (i.e. V2a and V2b). Signal

fractions a1 and b1 pass to first and second -180 degree phase shifters 128_1 and 128_2 respectively. Signal fractions a2 and b3 pass to A and B inputs of a first 180 degree hybrid coupler 134_1 of the kind described earlier. Signal fractions b2 and a3 pass to A and B inputs of a second coupler 134_2. The couplers 134_1 and 134_2 have A-B outputs connected as inputs to third and fourth splitters 124_3 and 124_4, which produce two-way splitting into signal fractions c1/c2 and d1/d2 respectively. They also have A+B outputs connected to A inputs of third and fourth couplers 134_3 and 134_4 respectively.

Output signals from the first and second phase shifters 128_1 and 128_2 pass to fifth and sixth splitters 124_5 and 124_6 producing three-way splitting into signal fractions e1/e2/e3 and f1/f2/f3 respectively. Output signals from the third splitter 124_3 pass (c1) to an A input of a fifth coupler 134_5 and (c2) to a third -180 degree phase shifter 128_3. Output signals from the fourth splitter 124_4 pass (d1) to an A input of a sixth coupler 134_6 and (d2) to a fourth -180 degree phase shifter 128_4. Output signals from the fifth splitter 124_5 pass (e1) to a B input of the fifth coupler 134_5, (e2) to a fifth -180 degree phase shifter 128_5 and (e3) to a B input of the fourth coupler 134_4. Output signals from the sixth splitter 124_6 pass (f1) to a B input of the sixth coupler 134_6, (f2) to a sixth -180 degree phase shifter 128_6 and (f3) to a B input of the third coupler 134_3. Via respective fixed phase shifters (PS) 136_1 to 136_{12}, the antenna elements 122_1 to 122_{12} receive drive signals from outputs of the third to sixth couplers 134_3 and 134_6 and third to sixth phase shifters 128_3 and 128_6 as set out in Table 3 below. Because all the terms a1 to f3 are fractions, all signal powers are in terms of fractions of original signals V2a and V2b (with phases as a and b) input to the first and second splitters 124_1 and 124_2 respectively. The -180 degree phase shifters 128_1 to 128_6 provide compensation for the 180 degree phase shift that takes place in a coupler (e.g. 134_1). Consequently, signals or signal components that do not pass via one or more couplers traverse two phase shifters (e.g. 128_1) and receive a phase shift of 360 degrees before reaching antenna elements 122_3 and 122_9. In addition, signals or signal components that pass via one coupler traverse one phase shifters (e.g. 128_4) and receive a relative phase shift of 180 degrees before reaching antenna elements (e.g. 122_2).

Table 3

Antenna Element	Coupler or Phase Shifter	Signal Power
122_1	Coupler 134_6, A-B output	d1(b2 - a3) - b1f1
122_2	Phase Shifter 128_4	d2(b2 - a3)
122_3	Coupler 134_6, A+B output	d1(b2 - a3) + b1f1
122_4	Phase Shifter 128_6	b1f2
122_5	Coupler 134_4, A-B output	b2 + a3 - e3
122_6	Coupler 134_4, A+B output	b2 + a3 + e3
122_7	Coupler 134_3, A+B output	a2 + b3 + f3
122_8	Coupler 134_3, A-B output	a2 + b3 - f3
122_9	Phase Shifter 128_5	a1e2
122_{10}	Coupler 134_5, A+B output	c1(a2 - b3) + a1e1
122_{11}	Phase Shifter 128_4	c2(a2 - b3)
122_{12}	Coupler 134_5, A-B output	c1(a2 - b3) - a1e1

Table 4 gives a1 to f3; voltages are calculated from powers normalised to sum to 1 watt.

Table 4

Splitter	Splitter Output	Splitter Ratios	
		Voltage	Decibels
124_1, 124_2	a1, b1	0.4690	-6.58
	a2, b2	0.8290	-1.63
	a3, b3	0.3040	-10.34
124_3, 124_4	c1, d1	0.800	-1.94
	c2, d2	0.600	-4.43
124_5, 124_6	e1, e3, f1, f3	0.2357	-12.55
	e2, f2	0.9428	--0.51

Referring now also to Figure 8, there is shown a vector diagram for the antenna system 120 when the phase difference between feeder signals V2a and V2b (with phases as a and b respectively) is sixty degrees, which is the angle at which the phase front of the antenna 122 is optimised.. Antenna element drive signals are indicated in magnitude and phase by solid radius vector arrows with antenna element reference numerals 122_1 to 122_{12} and signal powers (e.g. a1e2). Components (e.g. a1e1) of such signals are indicated by chain or dotted line vectors. Signals b1f2 and a1e2 on respective antenna elements 122_4 and 122_9 are fractions of and are in phase with input or feeder signals V2a and V2b, and they are sixty degrees apart in phase as indicated by two curved arrows each marked 30 degrees. This drawing contains full information regarding signal magnitude and phase, and will not be described further.

Figure 9 shows an implementation of a 180 degree fixed phase shift using a two-way splitter 140 and a 180 degree hybrid coupler 142 of the kind described earlier. The splitter 140 splits an input signal at 144 into two equal parts which are fed respectively to A and B inputs of the coupler 142. The coupler provides output from its A+B output, and its A-B output is terminated in a matched load 146. Strictly speaking the A-B output should be zero if the splitter 140 divides its input signal into accurately equal parts, but the load 146 will accommodate any inaccuracy in this regard. This arrangement allows the antenna system of the invention to operate over a range of frequencies, because the phase shifters and couplers are implemented similarly and will not differ substantially in time delay or phase properties as a function of frequency.

Referring now to Figure 10, an antenna system 150 of the invention is shown for a phased array 152 of n elements 152_1 to 152_n employing double variable delay, n being an arbitrary positive integer. A first splitter 154_1 receives an input signal Vin, and splits it into two equal signals which are routed to a first variable phase shifter 156_1 and a first fixed phase shifter 158_1 respectively. The first fixed phase shifter 158_1 provides an output signal via a second fixed phase shifter 158_2 to a second splitter 154_2, which splits it into n signal fractions a1 to a[n] for output via a bus indicated by Path A. The first variable phase shifter 156_1 provides an output signal to a third splitter 154_3 which splits it into n signal fractions b1 to b[n]. Signal fractions b2 to b[n] are output via a third first fixed phase shifter 158_3 and a bus indicated by Path B. Signal fraction b1 is routed to a second variable phase shifter 156_2 and thence to a fourth splitter 154_4, which splits it into n signal fractions c1 to c[n] for output via a bus indicated by Path C. The buses indicated by Paths A, B and C have Na, Nb and Nc individual conductors respectively.

The signal fractions on Paths A, B and C pass to a signal combining and phase shifting network indicated generally by 159. The network 159 is similar to that described with reference to Figures 3 and 4, and will not be described further. It has the function of combining and phase shifting signals to produce antenna element drive signals that vary appropriately for the phased array 152. The use of two variable phase shifter 156_1 and 156_2 increases the range of angles over which the antenna can be tilted electrically as compared to the use of one such only. Figure 10 may be extended with additional combinations of variable phase shifters and splitters if a larger range of tilt is required: i.e. just as b1 is variably phase shifted at 156_2 and split at 154_4, c1 may be variably phase shifted and split to produce d1 to d[n], d1 may be variably phase shifted and split to produce e1 to e[n], and so on.

Referring now to Figure 11, there is shown an antenna system 170 of the invention for a phased array 172 of ten elements 172_1 to 172_{10} employing ganged double variable delay. It is a variant of the system 150 described with reference to Figure 10, and employs phase shifters described with reference to Figure 9. A first splitter 174_1 receives an input signal Vin, and splits it into two equal signals which are routed to a first variable phase shifter 176_1 and a first -180 degree phase shifter 178_1. This phase shifter 178_1 compensates for phase shifts introduced in other signals in signal combining networks to be described below. It provides an output signal to a second splitter 174_2, which splits the output signal into four fractions a1 to a4. The first variable phase shifter 176_1 provides an output signal to a third splitter 174_3 which splits that output signal into two equal signals: one of these two signals passes to a fourth splitter 174_4 which splits it into three fractions b1 to b3. The other of these two signals passes via a second variable phase shifter 176_2 to a fifth splitter 174_5, which also splits it into three fractions c1 to c3.

Signal fractions b1 and c1 pass to antenna elements 172_3 and 172_8 via antenna phase shifters 182_3 and 182_8 respectively. Signal fractions b2, b3, c2 and c3 respectively provide A input signals to first, second, third and fourth 180 degree hybrid couplers 180_1, 180_2, 180_3 and180_4 of the kind described earlier. These couplers are the signal combining networks as mentioned above. Signal fractions a1 to a4 provide B input signals to these couplers respectively. Via respective fixed phase shifters (PS) 182_1, 182_2, 182_4 to 182_7, 182_9 and 182_{10}, the antenna elements 172_1, 172_2, 172_4 to 172_7, 172_9 and 172_{10} receive drive signals from outputs of the couplers 180_1 to 180_4 with amplitudes as set out in Table 4 below, to which the equivalents for elements 172_3 and 172_8 have

been added. Here N/A means not applicable. As all the terms a1 to c3 are fractions, all signal amplitudes are in terms of fractions of the original input signal Vin.

Table 5

Antenna Element	Coupler Output	Signal Power
172_1	Coupler 180_2, A+B output	b3 + a2
172_2	Coupler 180_1, A+B output	b2 + a1
172_3	N/A	b1
172_4	Coupler 180_1, A-B output	b2 - a1
172_5	Coupler 180_2, A-B output	b3 - a2
172_6	Coupler 180_4, A+B output	c3 + a4
172_7	Coupler 180_3, A+B output	c2 + a3
172_8	N/A	c1
172_9	Coupler 180_3, A-B output	c2 - a3
172_{10}	Coupler 180_4, A-B output	c3 - a4

Values of a1 to f3 are given in Table 6 below, where as before voltages have been calculated from powers normalised to sum to 1 watt.

Table 6

Splitter	Splitter Output	Splitter Ratios	
		Voltage	Decibels
174_2	a1, a3	0.3162	-10.00
	a2, a4	0.6324	-3.98
174_4	b1, b2, b3	0.577	-4.78
174_5	c1, c2, c3	0.577	-4.78

The variable phase shifters 176_1 and 176_2 are ganged as indicated by dotted lines so that they vary together and give equal phase shifts. They are controlled by a tilt control mechanism 186.

It can be seen from Figure 11 that only the upper half of the array 172 (antenna elements 172_6 to 172_{10}) receives signal contributions c1 etc from the fifth splitter 174_5, these contributions having undergone two variable phase shifts at 176_1 and 176_2. Moreover, only the lower half of the array 172, i.e. antenna elements 172_1 to 172_5, receive signal contributions b1 etc from the fourth splitter 174_5, these contributions having undergone one variable phase shift at 176_1. Both halves of the array 172 (other than antenna elements 172_3 and 172_8) receive signal contributions a1 etc from the second splitter 174_2, these contributions not having undergone a variable phase shift at 176_1 or 176_2.

Referring now to Figure 12, the antenna system of the invention may be implemented as a single feeder system or a dual feeder system. In a single feeder system, a single signal input 200 supplies a signal Vin via a feeder 202 to an antenna assembly 204 which may be mounted on a mast with an antenna array 206. Signal splitting, variable and fixed phase shifting and vectorial combining as described earlier is implemented in the assembly 204. This has the advantage that only one signal feed is needed to pass to the antenna system from a remote user, but against that a remote operator cannot adjust the angle of electrical tilt without access to the antenna assembly 204. Also, operators sharing a single antenna would all have the same angle of electrical tilt.

Figure 13 shows an antenna system of the invention implemented as a dual feeder system 210. This system has a tilt control section 212 which generates two signals V2a and V2b as described earlier, and these signals are fed via respective feeders 214A and 214B to an antenna assembly 216. The tilt control section 212 may be located with a user remotely from the antenna array 60, and an antenna feed network 218 (see e.g. figure 4) is located with the antenna array. Signal splitting, fixed phase shifting (if desired further variable phase shifting also) and vector combining as described earlier is implemented in the assembly 216. The user may now have direct access to the tilt control section 212 to adjust the angle of electrical tilt.

In a dual feeder installation it is also convenient to reduce tilt sensitivity to lessen the effects of phase differences between feeders, e.g. a difference between the angle of

electrical tilt required by the operator and that at the antenna. With a respective tilt control section 212 located with each operator, and at an input side of a frequency selective combiner located at an operator's base station, it is possible to implement a shared antenna system with an individual angle of tilt for each operator.

Figure 14 shows a phased array antenna system 240 of the invention equivalent to that shown in Figure 3 with modification for use in both receive and transmit modes. Parts previously described are like-referenced with a prefix 200 and only changes will be described. A variable phase shifter 246 with which tilt is controlled is now used in transmit (Tx) mode only, and is connected in a transmit path 243 between and in series with bandpass filters (BPF) 245 and 247. There is also a similar receive (Rx) path 249 with a variable phase shifter 251 between and in series with bandpass filters 253 and 255 and a low noise amplifier 257. Transmit and receive frequencies are normally sufficiently different to allow them to be isolated from one another by bandpass filters 255 *etc.* All elements 242 to 265 have the capability of operating in reverse in receive mode with e.g. splitters becoming combiners. The only difference been the two modes is that in transmit mode a feeder 265 provides input and transmit path 243 is traversed by a transmit signal from left to right, whereas in receive mode receive path 249 is traversed by a receive signal from right to left and feeder 265 provides output. The receive signal is generated in circuitry 26 to 264_n by phase shifting and combining antenna element signals generated by the array 262 in response to receipt of a signal from fee space. The system 240 is advantageous because it allows angles of electrical tilt in both transmit and receive modes to be independently adjustable and to be made equal: normally (and disadvantageously) this is not possible because antenna system components have frequency dependent properties which differ between transmit and receive frequencies.

Referring now to Figure 15, a phased array antenna system 300 of the invention is shown for use in transmit and receive modes by multiple (two) operators 301 and 302 of a single phased array antenna 305. Parts equivalent to those previously described are like-referenced with a prefix 300. The drawing has a number of different channels: parts in different channels which are equivalent are numerically like-referenced with one or more suffixes: a suffix T or R indicates a transmit or receive channel, a suffix 1 or 2 indicates first or second operator 301 or 302, and a suffix A or B indicates A or B path. Omission of these suffixes from a reference numeral prefix (e.g. 342) means that all items having that prefix are referred to.

Initially a transmit channel 307T1 of the first operator 301 will be described. This transmit channel has an RF input 342 feeding a splitter 344T1, which divides the input between variable and fixed phase shifters 346T1A and 348T1B. Signals pass from the phase shifters 346T1A and 348T1B to bandpass filters (BPF) 309T1A and 309T1B in different duplexers 311A and 311B respectively. The bandpass filters 309T1A and 309T1B have pass band centres at a frequency of transmission of the first operator 301, this frequency being designated Ftx1 as indicated in the drawing. The first operator 301 also has a frequency of reception designated Frx1, and equivalents for the second operator 302 are Ftx2 and Frx2.

The first operator transmit signal at frequency Ftx1 output from the leftmost bandpass filter 309T1A is combined by the first duplexer 311A with a like-derived second operator transmit signal at frequency Ftx2 output from an adjacent bandpass filter 309T2A. These combined signals pass along a feeder 313A to an antenna tilt network 315 of the kind described in earlier examples, and thence to the phased array antenna 305. Similarly, the other first operator transmit signal at frequency Ftx1 output from bandpass filter 309T1B is combined by the second duplexer 311B with a like-derived second operator transmit signal at frequency Ftx2 output from an adjacent bandpass filter 309T2B. These combined signals pass along a second feeder 313B to the phased array antenna 305 via the antenna tilt network 315. Despite using the same phased array antenna 305, the two operators can alter their transmit angles of electrical tilt both independently and remotely from the antenna 305 merely by adjusting variable phase shifters 346T1A and 346T2A respectively.

Analogously, receive signals returning from the antenna 305 via network 315 and feeders 313A and 313B are divided by the duplexers 311A and 311B. These divided signals are then filtered to isolate individual frequencies Frx1 and Frx2 in bandpass filters 309R1A, 309R2A, 309R1B and 309R2B, which provide signals to variable and fixed phase shifters 346R1A, 346R2A, 348R1B and 348R2B respectively. Receive angles of electrical tilt are then adjustable by the operators 301 and 302 independently by adjusting their respectively variable phase shifters 346R1A and 346R2A. Signals for more than two operators may be combined in transmission or separated in reception by replicating components: i.e. instead of components with suffixes 1 and 2 there would be like components with suffixes 1 to m where m is the number of operators.

Figure 16 shows a phased array antenna system 470 of the invention largely the same as that shown in Figure 11. Parts previously described are like-referenced with a prefix 400 replacing 100 and only modifications will be described. The system 470 has a first splitter 474_1 which splits an input RF carrier signal at 473 into two parts, one of which passes via a first variable phase shifter 476_1 to a first feeder 477_1 and the other directly to a second feeder 477_2. The items 473 to 477_2 are located in or near a cellular mobile radio base station (not shown). The feeders 477_1 and 477_2 connect the base station to a remote antenna radome 479, in which a second variable phase shifter 476_2 is located.

The system 470 operates as described earlier with reference to Figure 11, except that the first and second variable phase shifters 476_1 and 476_2 are no longer ganged but instead are adjusted independently. It provides the advantage that an individual angle of electrical tilt can be provided for each operator sharing the antenna 472 (using frequency selective combining such as that shown in Figure 15) but the tilt range, common to all operators, is extended. In practice the angle of electrical tilt set by the second variable phase shifter 476_2 may conveniently be the average of the individual angles of electrical tilt of all the operators sharing the antenna 472.

Whereas Figure 16 shows adjustment of the second variable phase shifter 476_2 within the antenna radome 479, It may also be set remotely from the radome 479 using a servo mechanism controller (not shown). Further variable phase shifters may be added to the antenna system 470 in accordance with the invention to extend further the range of tilt common to all operators.

Claims

1. A phased array antenna system with adjustable electrical tilt and comprising an array (62) of antenna elements (62_1 to 62_n) characterised in that the system (60) incorporates:
   a) a variable phase shifter (46) for introducing a variable relative phase shift between first and second RF signals,
   b) splitting apparatus (52, 54) for dividing the relatively phase shifted first and second signals into component signals, and
   c) a signal combining and phase shifting network (56 to 64_n) for vectorially combining and relatively phase shifting the component signals to provide drive signals with appropriate relative phasing for the antenna elements (62_1 to 62_n).

2. A system according to Claim 1 characterised in that it has an odd number of antenna elements (62_0 to 62_{10}) comprising a central antenna element (62_0) separated from adjacent antenna elements (62_5, 62_6) by a distance which is half that between other adjacent antenna element pairs ($62_i/62_{i+1}$, i = 1 to 4 and 6 to 9).

3. A system according to Claim 1 characterised in that the variable phase shifter is a first variable phase shifter (156_1) and the system includes a second variable phase shifter (156_2) arranged to phase shift a component signal (b1) which has been phase shifted by the first variable phase shifter (156_1), the second variable phase shifter (156_2) providing a further component signal output for the signal combining and phase shifting network (159) either directly or via one or more splitter/variable phase shifter combinations.

4. A system according to Claim 1 characterised in that the variable phase shifter is a one of a plurality of variable phase shifters (176_1, 176_2), and the signal phase shifting and combining network is arranged to produce antenna element drive signals from component signals some of which (c1 to c3) have passed through all the variable phase shifters (176_1, 176_2) and some of which have not.

5. A system according to Claim 1 characterised in that the splitting apparatus (154_2, 154_3, 154_4) is arranged to divide a component signal into further component signals for input to the signal phase shifting and combining network (180).

6. A system according to Claim 1 characterised in that the signal phase shifting and combining network (56 to 64_n) employs phase shifters (56, 58) and hybrid couplers (60_1 to 62_4) for phase shifting and vectorially combining the component signals.

7. A system according to Claim 6 characterised in that the hybrid couplers are 180 degree hybrid couplers (60_1 to 62_4).

8. A system according to Claim 6 characterised in that the hybrid couplers (60_1 to 62_4) are designed to convert input signals A and B into vector sums other than (A+B) and (A-B).

9. A system according to Claim 6 characterised in that each phase shifter is implemented by a splitter (140) and a 180 degree hybrid coupler (142) having a sum output (A+B) for providing a phase shifted signal and a difference output (A-B) terminated with a matched load (146).

10. A system according to Claim 1 characterised in that the splitting apparatus (52, 54), variable phase shifter, and the signal phase shifting and combining network are co-located with the antenna array (206) as an antenna assembly (204), and the assembly (204) has a single RF input power feeder (202) from a remote source.

11. A system according to Claim 1 characterised in that the splitting apparatus incorporates first, second and third splitters, the first splitter is located with the variable phase shifter remotely from the second and third splitters, and the second and third splitters, the signal phase shifting and combining network and the antenna array (216) are co-located as an antenna assembly (216, 218), and the assembly (216, 218) has dual RF input power feeders (214A, 214B) from a remote source (212) at which the first splitter and variable phase shifter are located.

12. A system according to Claim 1 characterised in that the variable phase shifter is a first variable phase shifter (246) connected in a transmit channel (243), and the system includes a second variable phase shifter (251) connected in a receive channel (249) and the signal phase shifting and combining network is arranged to operate in both transmission and reception modes by producing antenna element drive signals in response to a signal in the transmit channel (243) and producing a receive channel signal from signals developed by antenna elements operating in reception mode.

13. A system according to Claim 1 characterised in that the variable phase shifter is one of a plurality of variable phase shifters (346T1A, 346T2A) associated with respective operators, and the system includes filtering and combining apparatus (311A) for routing signals on to common signal feed apparatus (313A, 313B) after phase shifting in respective variable phase shifters (346T1A, 346T2A), the common signal feed apparatus (313A, 313B) being connected to splitting apparatus (315) and a signal combining and phase shifting network (315) for providing signals to the antenna (305) containing contributions from both operators with independently adjustable electrical tilt.

14. A system according to Claim 13 characterised in that the plurality of variable phase shifters comprises a respective pair of variable phase shifters (346T1A, 346T1B, 346T2A, 346T2B) associated with each operator, and the system has components (305 to 346) which have both forward and reverse signal processing capabilities such that the system is operative in transmit and receive modes with independently adjustable electrical tilt in both modes.

15. A method of providing a phased array antenna system with adjustable electrical tilt, the system (60) including an array (62) of antenna elements (62_1 to 62_n), characterised in that the method incorporates:

a) introducing a variable relative phase shift between first and second RF signals,

b) dividing the relatively phase shifted first and second signals into component signals, and

c) vectorially combining and relatively phase shifting the component signals to provide drive signals with appropriate relative phasing for the antenna elements (62_1 to 62_n).

16. A method according to Claim 15 characterised in that the array (60) has an odd number of antenna elements (62_1 to 62_{10}) comprising a central antenna element (62_0) separated from adjacent antenna elements (62_5, 62_6) by a distance which is half that between other adjacent antenna element pairs ($62_i/62_{i+1}$, i = 1 to 4 and 6 to 9).

17. A method according to Claim 15 characterised in that it includes generating at least one component signal which has undergone phase shifting in a plurality of variable phase shifters (156_1, 156_2).

18. A method according to Claim 15 characterised in that the variable phase shifters (176_1, 176_2) are ganged, and the method includes producing antenna element drive signals from component signals some of which (c1 to c3) have passed through all the variable phase shifters (176_1, 176_2), and some of which have not.

19. A method according to Claim 15 characterised in that it includes dividing a component signal into further component signals for input to the signal phase shifting and combining network (180).

20. A method according to Claim 15 characterised in that it employs phase shifters (56, 58) and hybrid couplers (60_1 to 60_4) for phase shifting and vectorially combining the component signals.

21. A method according to Claim 20 characterised in that the hybrid couplers are 180 degree hybrid couplers (60_1 to 62_4).

22. A method according to Claim 20 characterised in that the hybrid couplers (60_1 to 62_4) are designed to convert input signals A and B into vector sums other than (A+B) and (A-B).

23. A method according to Claim 20 characterised in that each phase shifter is implemented by a splitter (140) and a 180 degree hybrid coupler (142) having a sum output (A+B) for providing a phase shifted signal and a difference output (A-B) terminated with a matched load (146).

24. A method according to Claim 15 characterised in that it includes feeding a single RF input signal from a remote source for splitting, variable phase shifting and vectorial combining in a network co-located with the antenna array (206) to form an antenna assembly (204).

25. A method according to Claim 15 characterised in that it includes feeding two RF input signals with variable phase relative to one another from a remote source (212) to an antenna assembly and splitting, combining and phase shifting signals in a network (218) co-located with the antenna array (216).

26. A method according to Claim 15 characterised in that it employs a transmit channel (243) and a receive channel (249) for operation in both transmission and reception modes, and it includes producing antenna element drive signals in response to a signal in the transmit channel (243) and producing a receive channel signal from signals developed by antenna elements operating in reception mode.

27. A method according to Claim 15 characterised in that the variable phase shifter is one of a plurality of variable phase shifters (346T1A, 346T2A) associated with respective operators, and the method includes:

a) filtering and combining signals on to common signal feed apparatus (313A, 313B) after phase shifting in respective variable phase shifters (346T1A, 346T2A), the common signal feed apparatus (313A, 313B) being connected to the splitting apparatus (315) and the signal combining and phase shifting network (315);

b) providing signals to the antenna (305) containing contributions from both operators; and

c) independently adjusting electrical tilt associated with each operator.

28. A method according to Claim 27 characterised in that the plurality of variable phase shifters comprises a respective pair of variable phase shifters (346T1A, 346T1B, 346T2A, 346T2B) associated with each operator, the method employs components (305 to 346) which have both forward and reverse signal processing capabilities, and the method includes operating in transmit and receive modes with independently adjustable electrical tilt in both modes.

ABSTRACT

A phased array antenna system with adjustable electrical tilt includes an array 62 of antenna elements 62_1 to 62_{10}.It has a divider 44 dividing a radio frequency (RF) carrier signal into two signals between which a phase shifter 46 introduces a variable phase shift. Splitters 52 and 54 divide the relatively phase shifted signals into two sets of five signals. Four of each of the sets of five signals are vectorially combined in a network of 180 degree hybrid couplers 60_1 to 60_4. This provides vector sum and difference components which together with the fifth members of the sets are fed to respective fixed phase shifters 56, 58 and 64_1 to 64_{10}. The phase shifters 64_1 to 64_{10} provide signals which are appropriately phased for use as phased array drive signals for respective antenna elements 62_1 to 62_{10}. Adjustment of the phase shift provided by the variable phase shifter 46 changes the angle of electrical tilt of the antenna array 62.

Figure 3 should accompany the Abstract..

Figure 1

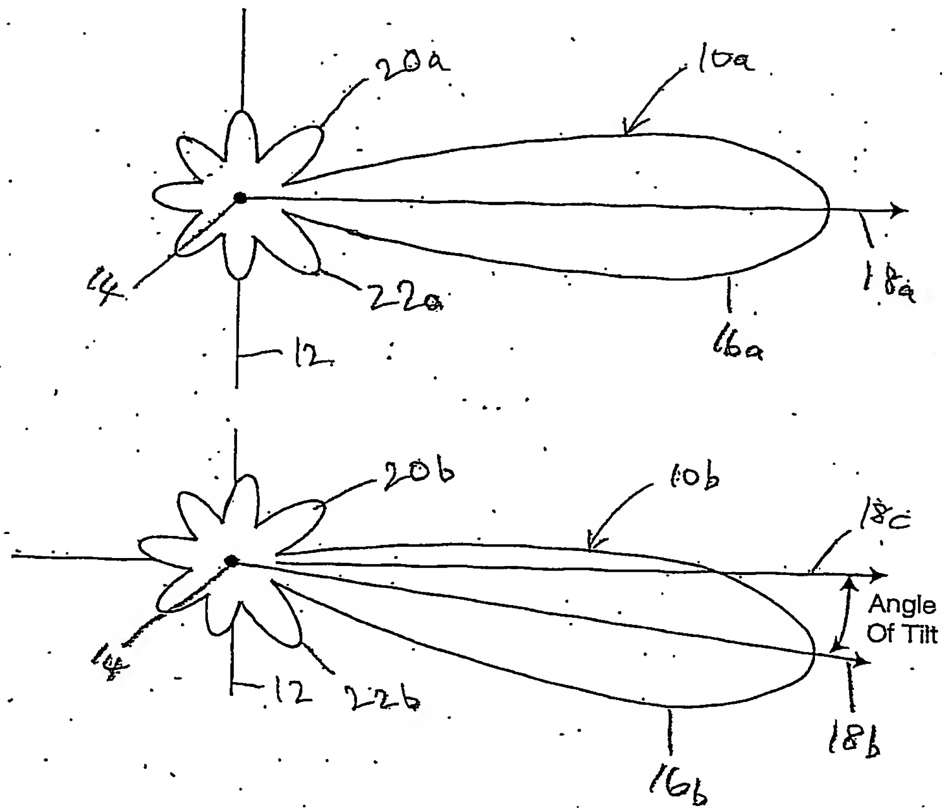
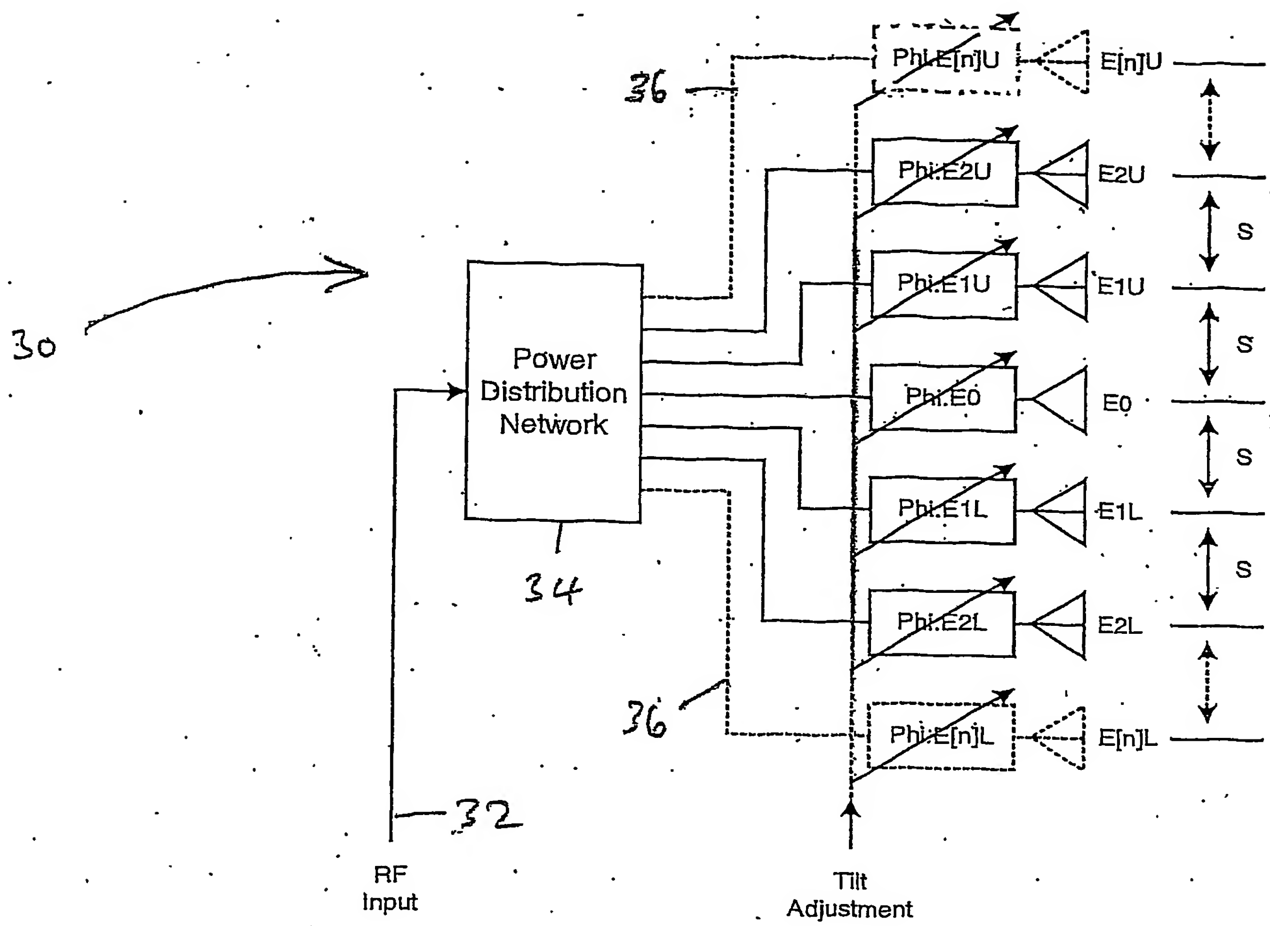

20a
10a
14
22a
12
16a
18a
20b
10b
18c
Angle
Of Tilt
14
12
22b
18b
16b

Figure 2 Prior Art



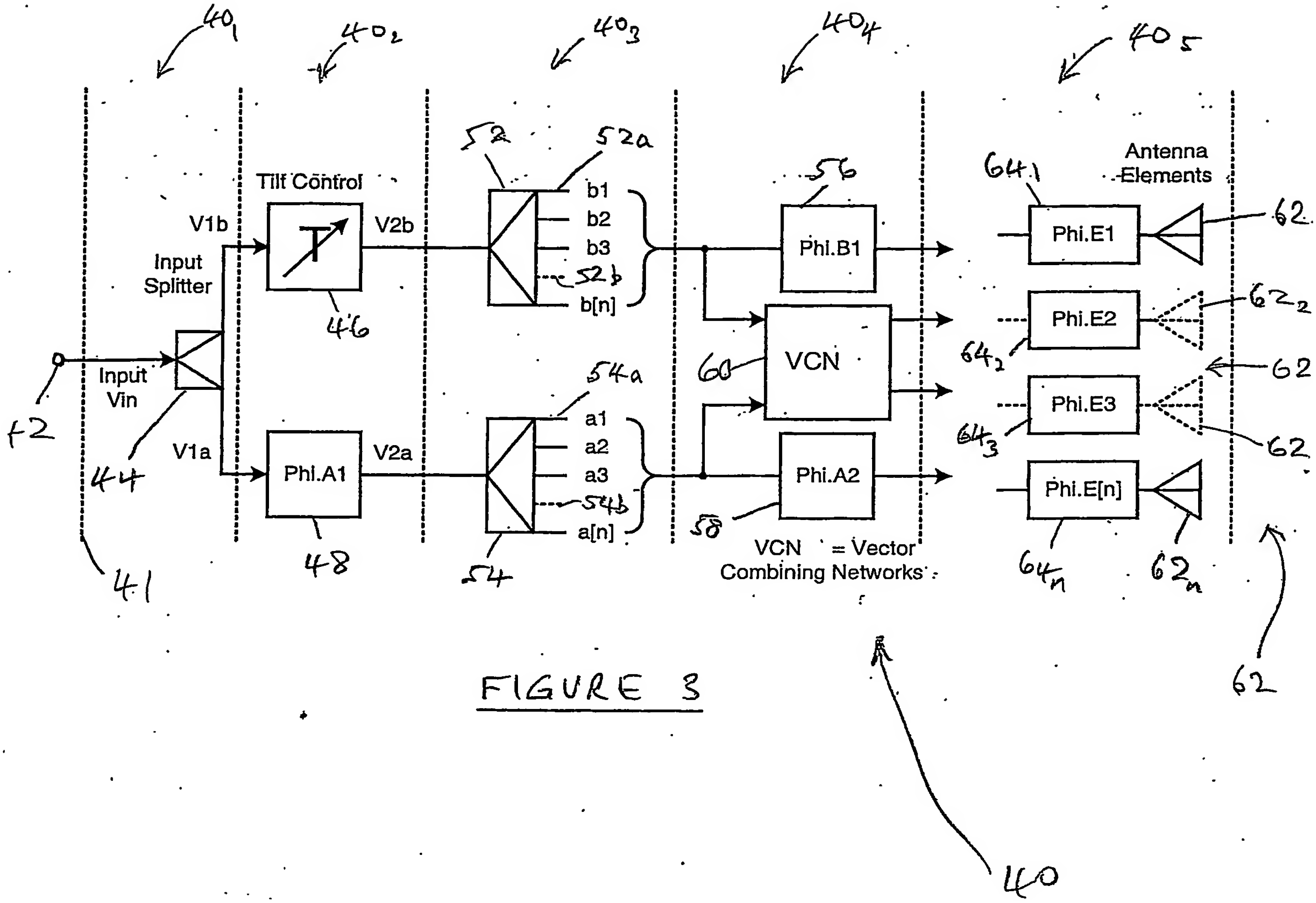

40₁
40₂
40₃
40₄
40₅
Tilt Control
Antenna Elements
V1b
V2b
Input Splitter
b1
b2
b3
b[n]
52
52a
52b
56
Phi.B1
64₁
Phi.E1
62
62₂
Phi.E2
64₂
VCN
60
Phi.E3
64₃
Input Vin
42
44
V1a
Phi.A1
V2a
a1
a2
a3
a[n]
54a
54b
54
Phi.A2
58
Phi.E[n]
64ₙ
62ₙ
46
48
41
VCN = Vector Combining Networks
40

FIGURE 3

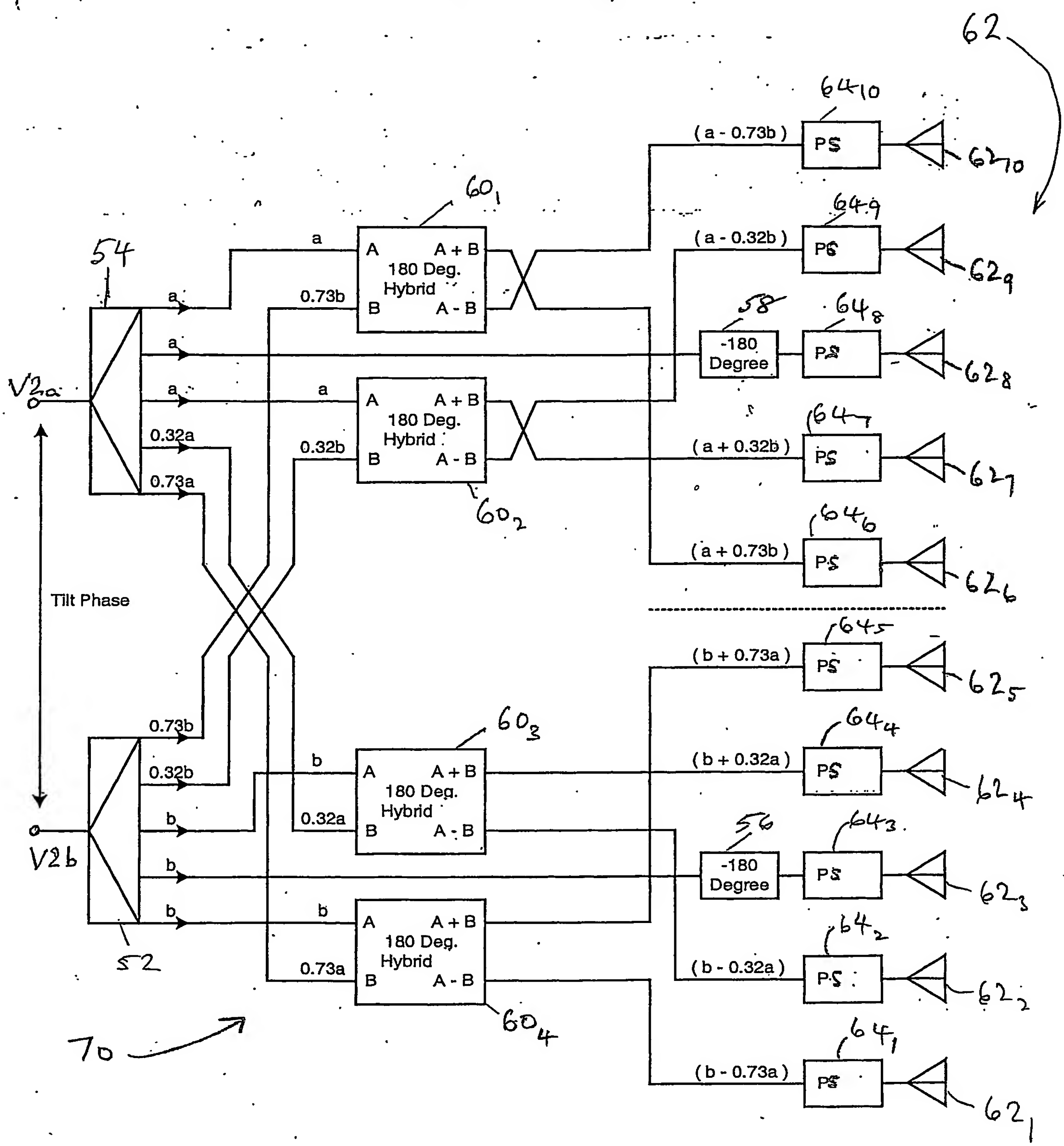
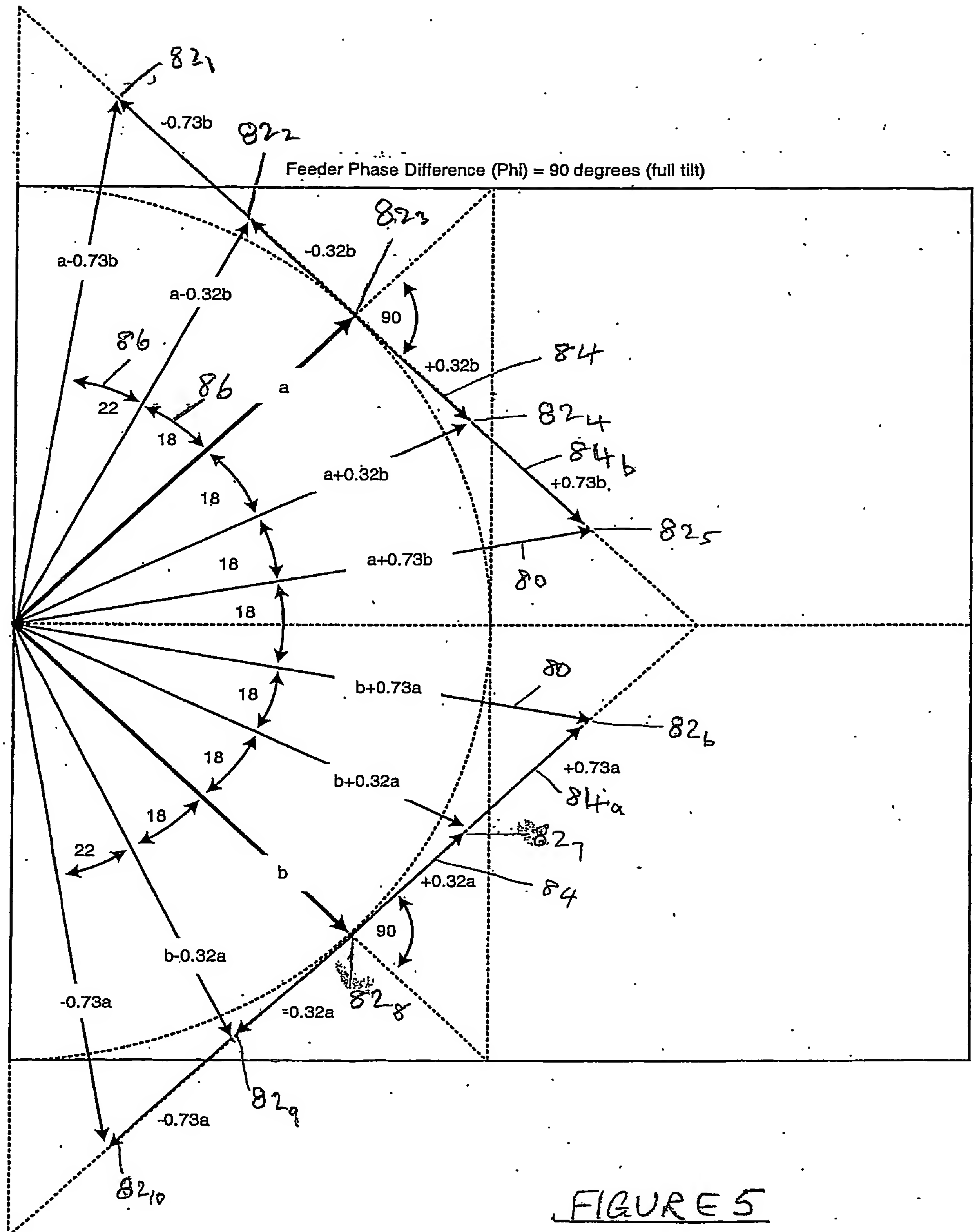

62
64_{10}
(a - 0.73b)
PS
62_{10}
60_1
64_9
(a - 0.32b)
PS
62_9
54
a
A
A + B
180 Deg.
Hybrid
B
A - B
0.73b
a
58
64_8
-180
Degree
PS
62_8
V2a
a
a
0.32a
0.73a
0.32b
64_7
(a + 0.32b)
PS
62_7
60_2
64_6
(a + 0.73b)
PS
62_6
Tilt Phase
64_5
(b + 0.73a)
PS
62_5
60_3
0.73b
0.32b
b
0.32a
64_4
(b + 0.32a)
PS
62_4
V2b
b
b
b
56
64_3
-180
Degree
PS
62_3
52
0.73a
64_2
(b - 0.32a)
PS
62_2
60_4
70
64_1
(b - 0.73a)
PS
62_1

FIGURE 4



82₁
-0.73b
82₂
Feeder Phase Difference (Phi) = 90 degrees (full tilt)
82₃
-0.32b
a-0.73b
a-0.32b
90
+0.32b
84
86
86
22
18
a
82₄
84b
18
a+0.32b
+0.73b
18
a+0.73b
82₅
80
18
18
b+0.73a
80
82₆
18
+0.73a
b+0.32a
84a
18
82₇
22
b
+0.32a
84
90
b-0.32a
82₈
-0.73a
=0.32a
82₉
-0.73a
82₁₀

FIGURE 5

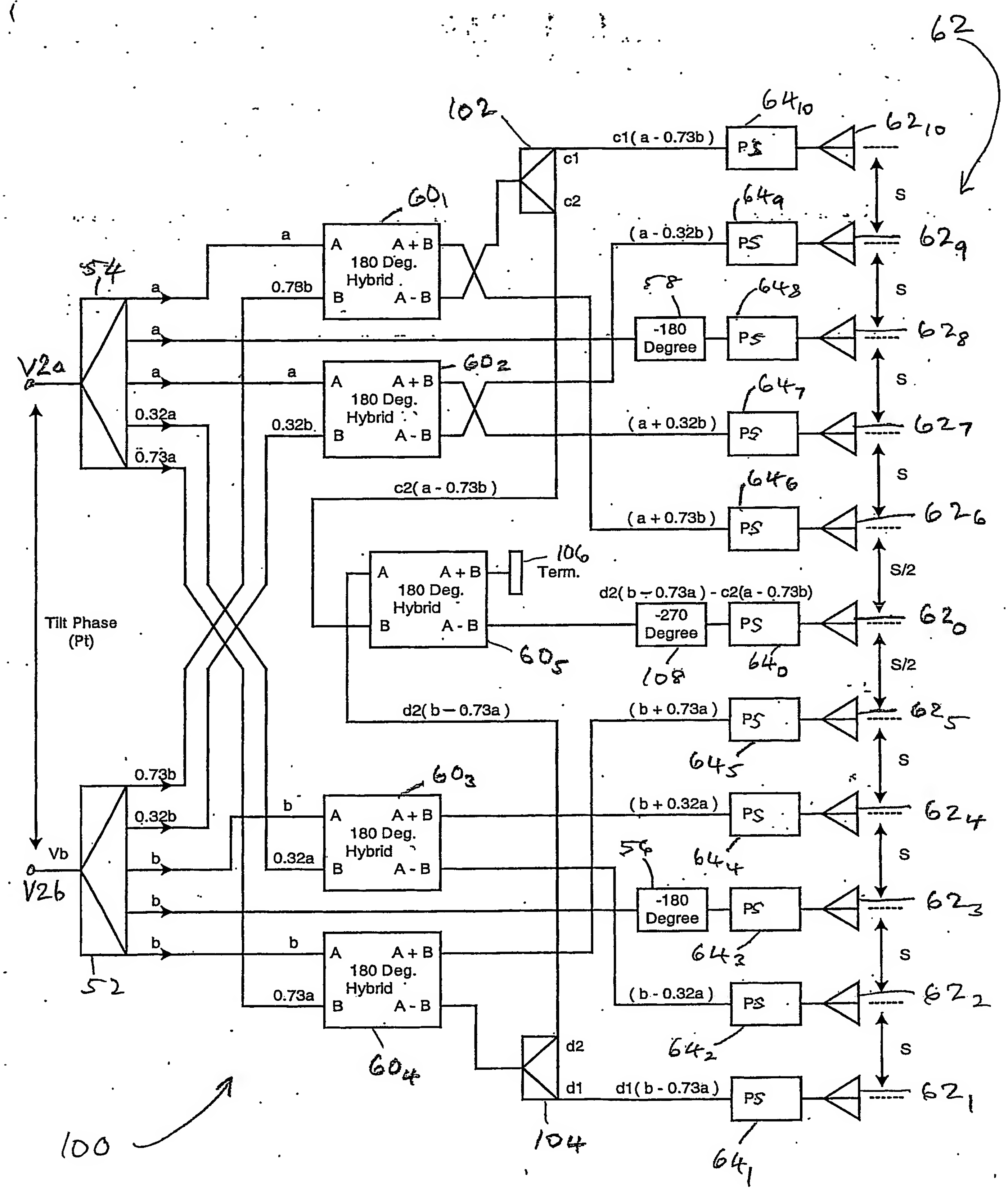

62
102
64_{10}
62_{10}
c1(a - 0.73b)
PS
c1
c2
60_1
64_9
(a - 0.32b)
62_9
S
54
a
A
A + B
180 Deg.
Hybrid
B
A - B
0.78b
58
64_8
-180
Degree
62_8
V2a
60_2
0.32a
0.32b
0.73a
64_7
(a + 0.32b)
62_7
c2(a - 0.73b)
64_6
(a + 0.73b)
62_6
106
Term.
d2(b - 0.73a) - c2(a - 0.73b)
-270
Degree
62_0
S/2
Tilt Phase
(Pt)
60_5
108
64_0
d2(b – 0.73a)
(b + 0.73a)
62_5
64_5
0.73b
60_3
b
(b + 0.32a)
62_4
Vb
V2b
56
64_4
62_3
64_3
52
(b - 0.32a)
62_2
64_2
d2
d1
d1(b - 0.73a)
62_1
60_4
100
104
64_1

FIGURE 6

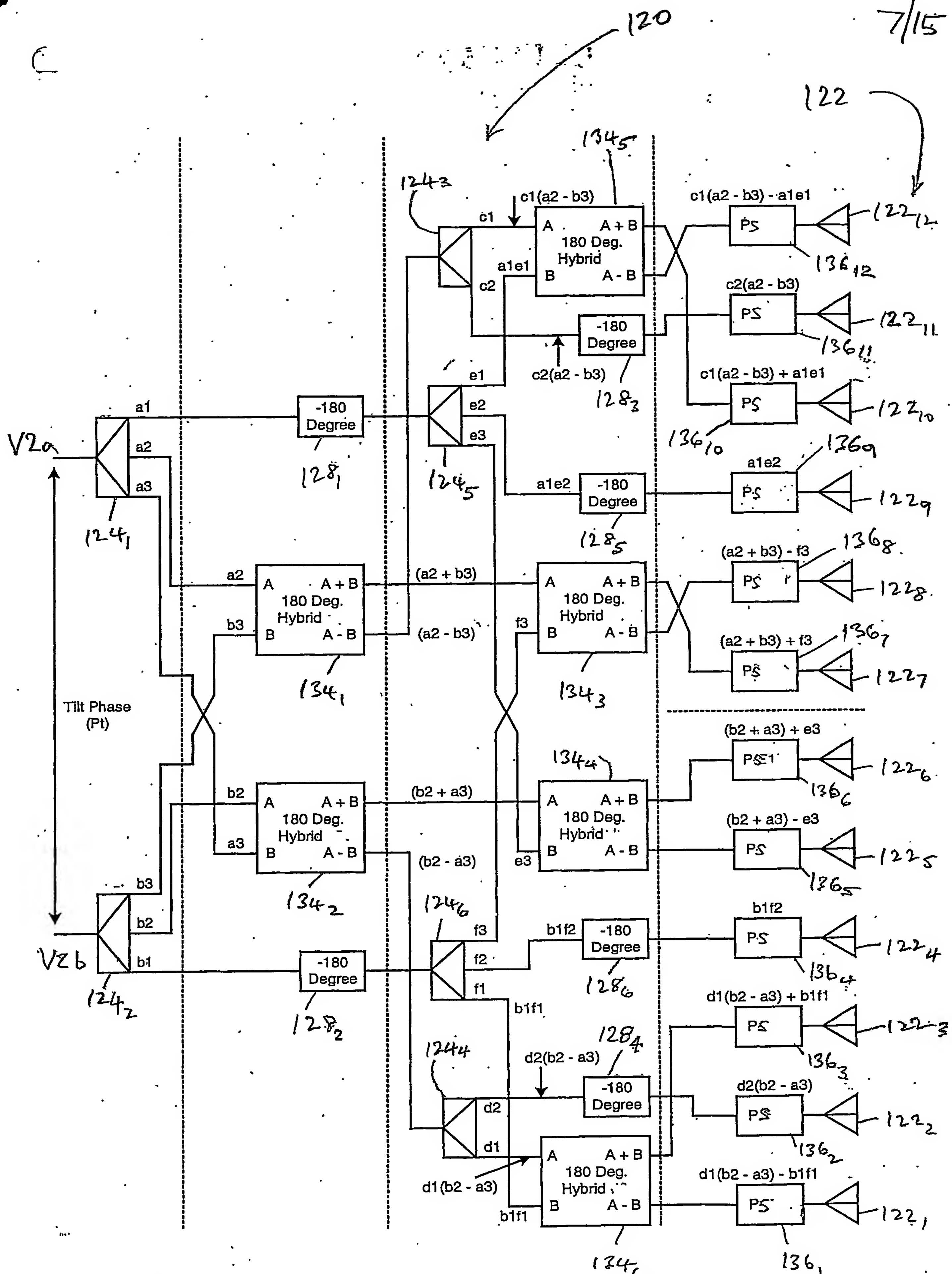

120
122
V2a
V2b
a1
a2
a3
b1
b2
b3
Tilt Phase
(Pt)
-180
Degree
180 Deg.
Hybrid
A
B
A + B
A - B
(a2 + b3)
(a2 - b3)
(b2 + a3)
(b2 - a3)
c1
c2
c1(a2 - b3)
c2(a2 - b3)
a1e1
a1e2
e1
e2
e3
f1
f2
f3
b1f1
b1f2
d1
d2
d1(b2 - a3)
d2(b2 - a3)
c1(a2 - b3) - a1e1
c1(a2 - b3) + a1e1
(a2 + b3) - f3
(a2 + b3) + f3
(b2 + a3) + e3
(b2 + a3) - e3
d1(b2 - a3) + b1f1
d1(b2 - a3) - b1f1
PS
1241
1242
1243
1244
1245
1246
1281
1282
1283
1284
1285
1286
1341
1342
1343
1344
1345
1346
1361
1362
1363
1364
1365
1366
1367
1368
1369
13610
13611
13612
1221
1222
1223
1224
1225
1226
1227
1228
1229
12210
12211
12212

FIGURE 7

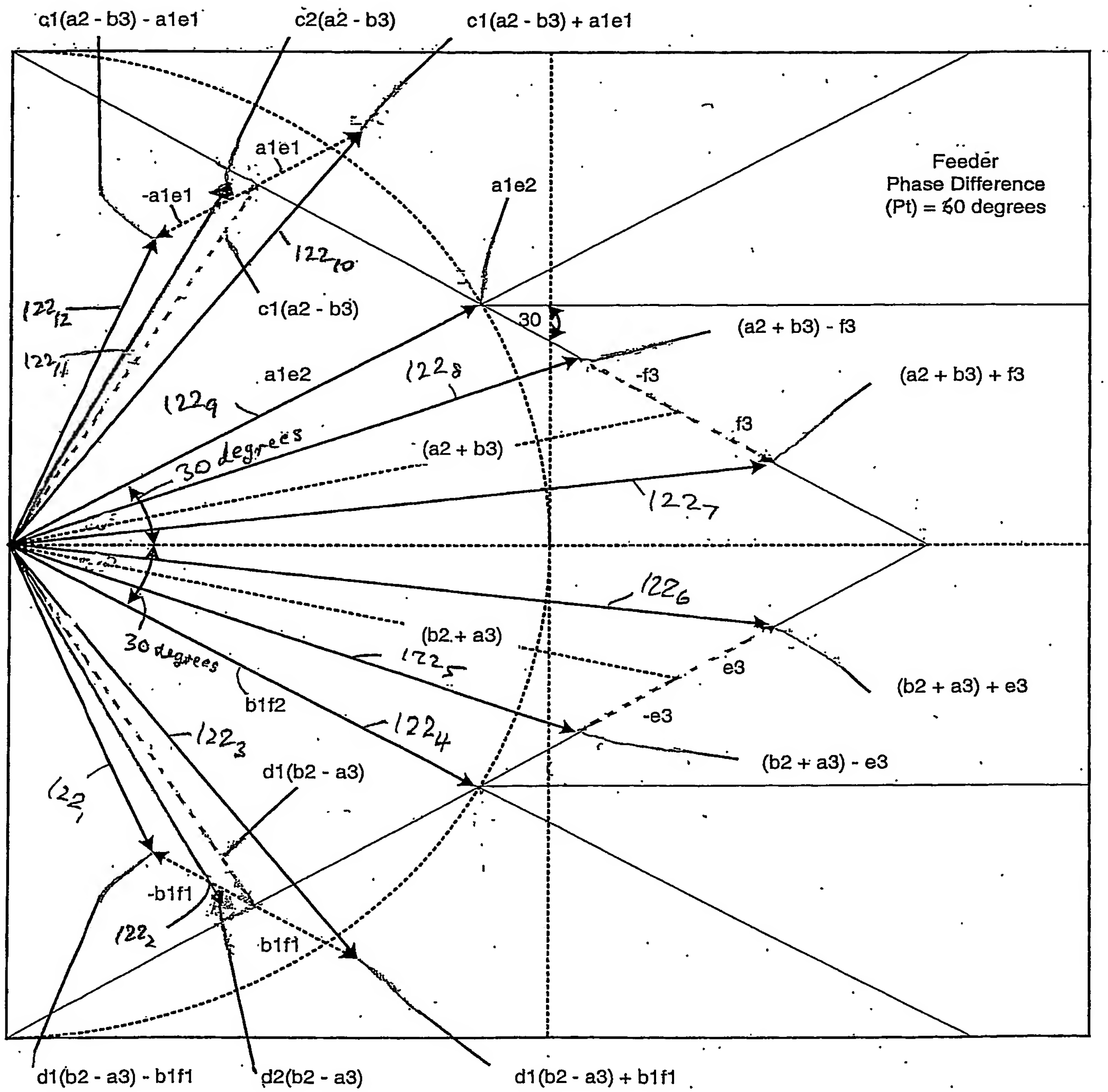

c1(a2 - b3) - a1e1
c2(a2 - b3)
c1(a2 - b3) + a1e1
a1e1
-a1e1
a1e2
Feeder
Phase Difference
(Pt) = 60 degrees
122_{10}
122_{12}
c1(a2 - b3)
30
(a2 + b3) - f3
122_{11}
a1e2
122_8
-f3
(a2 + b3) + f3
122_9
f3
30 degrees
(a2 + b3)
122_7
122_6
(b2 + a3)
30 degrees
122_5
e3
(b2 + a3) + e3
b1f2
-e3
122_4
122_3
(b2 + a3) - e3
d1(b2 - a3)
122_1
-b1f1
122_2
b1f1
d1(b2 - a3) - b1f1
d2(b2 - a3)
d1(b2 - a3) + b1f1

FIGURE 8

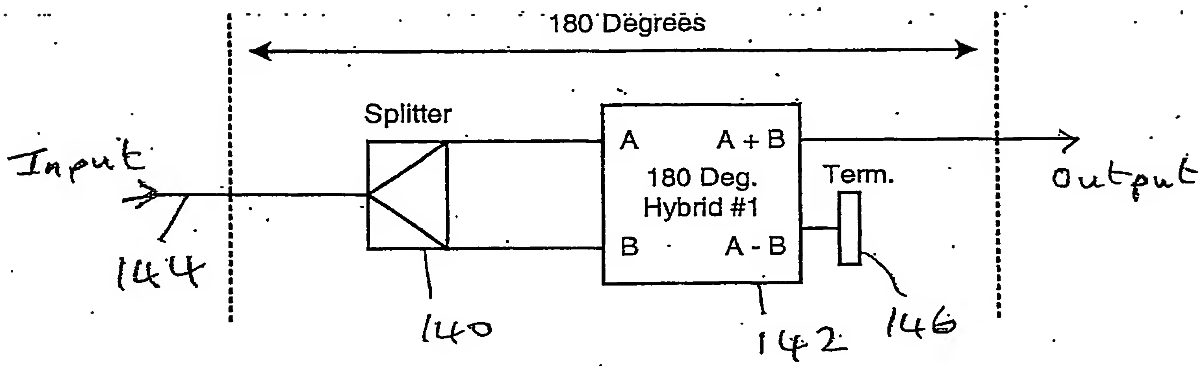

180 Degrees
Splitter
Input
144
140
A
A + B
180 Deg.
Hybrid #1
B
A - B
142
Term.
146
Output

FIGURE 9

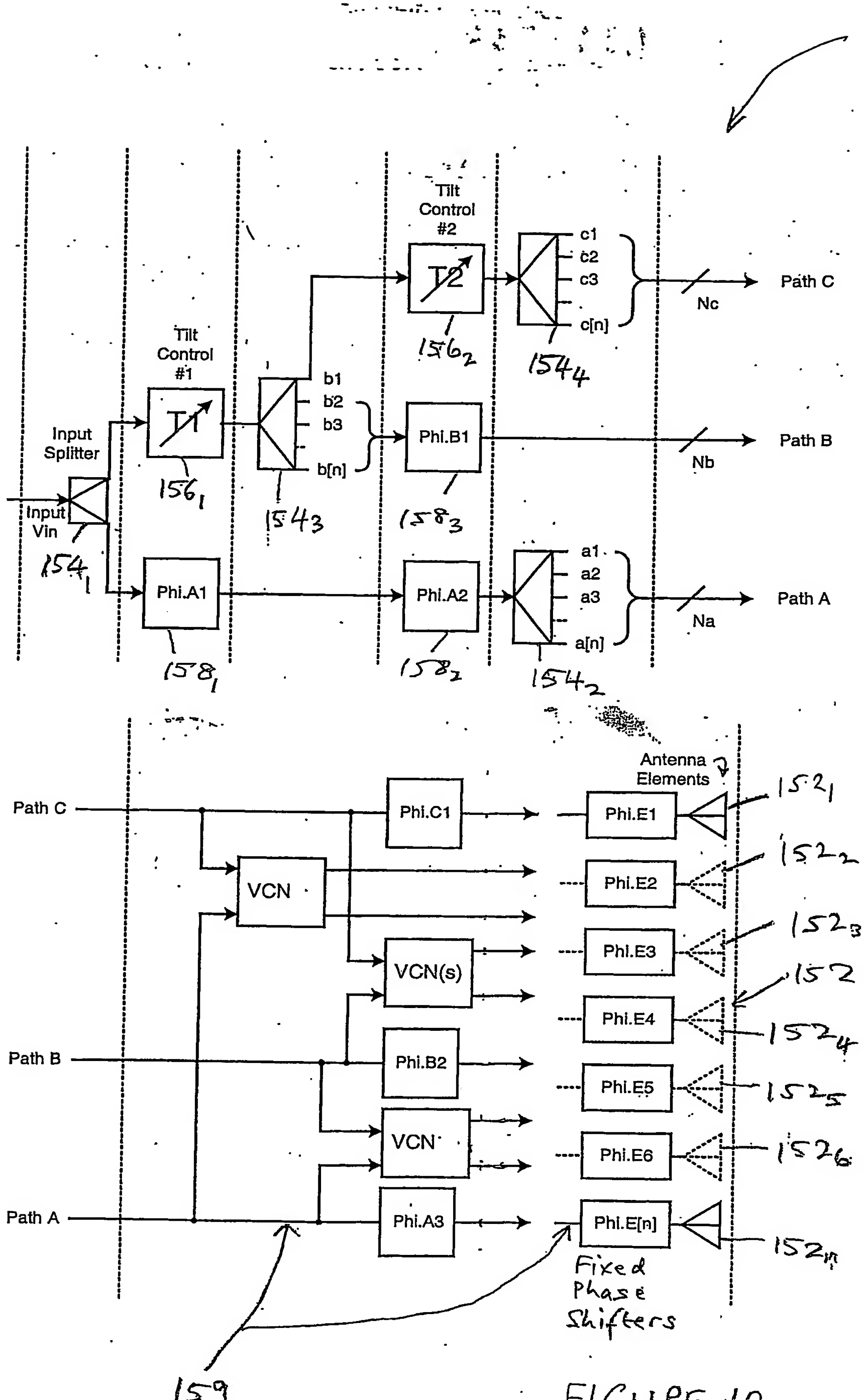

150
Tilt
Control
#2
T2
c1
c2
c3
c[n]
Path C
Nc
156₂
1544
Tilt
Control
#1
T1
b1
b2
b3
b[n]
Phi.B1
Path B
Nb
Input
Splitter
156₁
154₃
158₃
Input
Vin
154₁
Phi.A1
Phi.A2
a1
a2
a3
a[n]
Path A
Na
158₁
158₂
154₂
Antenna
Elements
Path C
Phi.C1
Phi.E1
152₁
VCN
Phi.E2
152₂
Phi.E3
152₃
VCN(s)
152
Phi.E4
152₄
Path B
Phi.B2
Phi.E5
152₅
VCN
Phi.E6
152₆
Path A
Phi.A3
Phi.E[n]
152ₙ
Fixed
Phase
Shifters
159

FIGURE 10

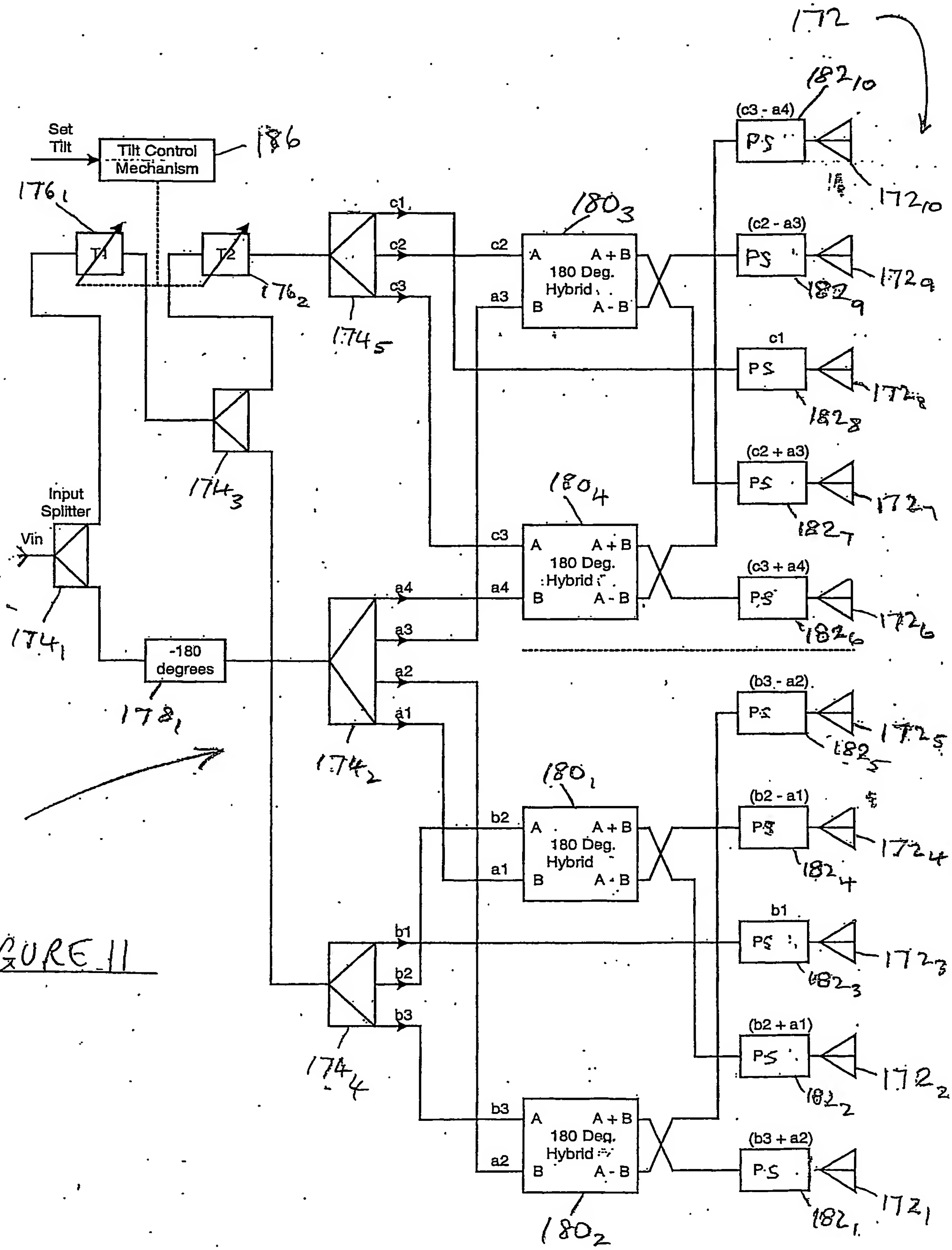
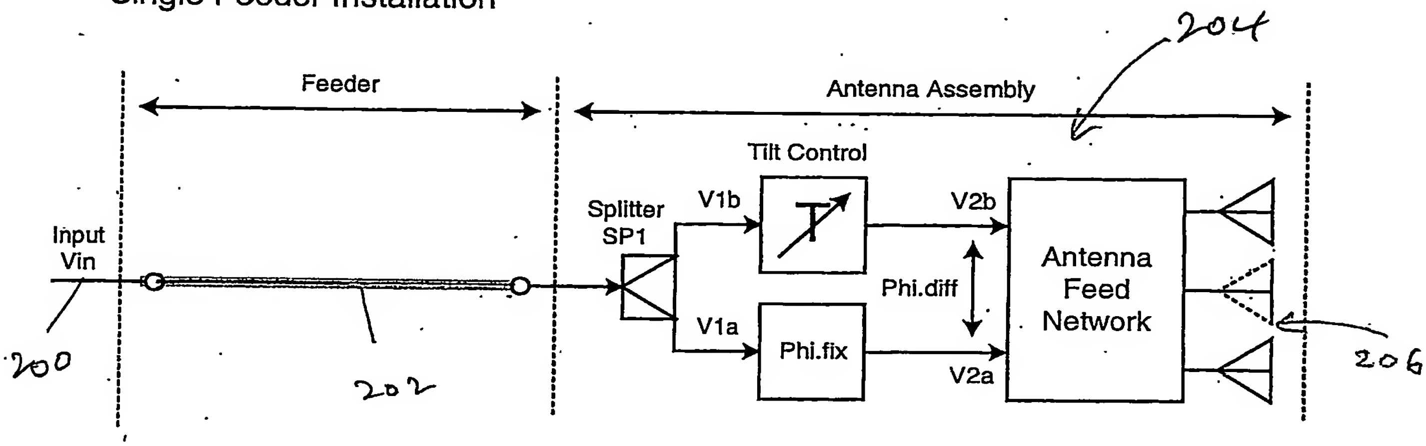

172
182₁₀
(c3 - a4)
PS
172₁₀
Set Tilt
Tilt Control Mechanism
186
176₁
T1
T2
176₂
c1
c2
c3
174₅
180₃
A
A + B
180 Deg. Hybrid
B
A - B
a3
(c2 - a3)
172₉
182₉
c1
172₈
182₈
174₃
(c2 + a3)
172₇
182₇
180₄
Input Splitter
Vin
174₁
a4
a3
a2
a1
(c3 + a4)
172₆
182₆
-180 degrees
178₁
174₂
(b3 - a2)
172₅
182₅
180₁
b2
a1
(b2 - a1)
172₄
182₄
170
b1
b2
b3
b1
172₃
182₃
174₄
(b2 + a1)
172₂
182₂
b3
a2
(b3 + a2)
172₁
182₁
180₂

FIGURE 11

FIGURE 12

Single Feeder Installation



Dual Feeder Installation

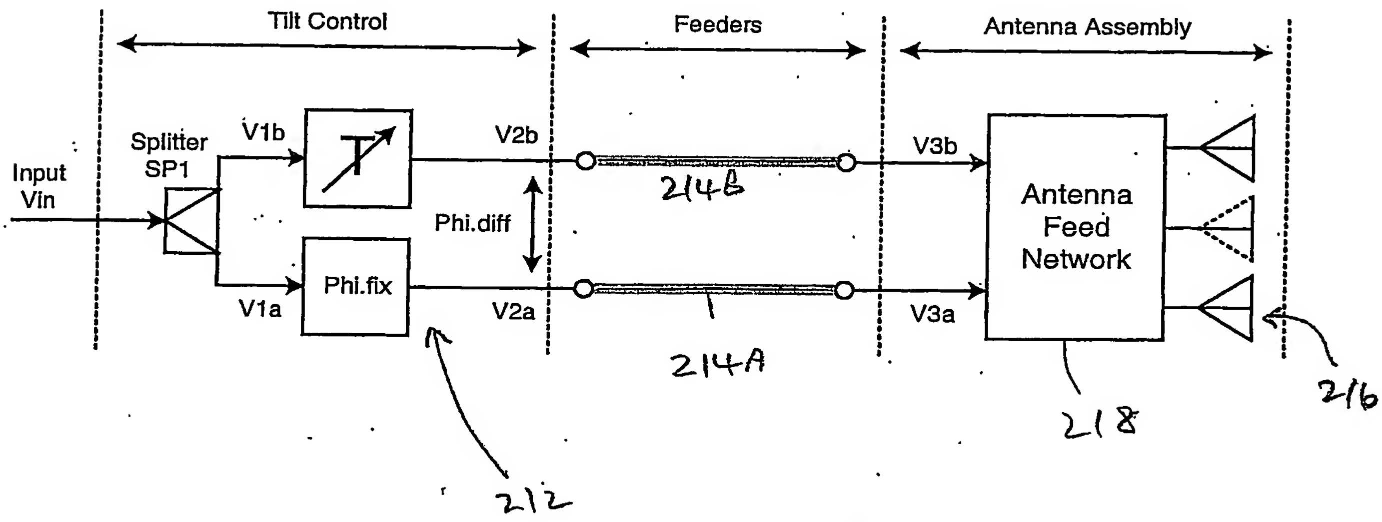
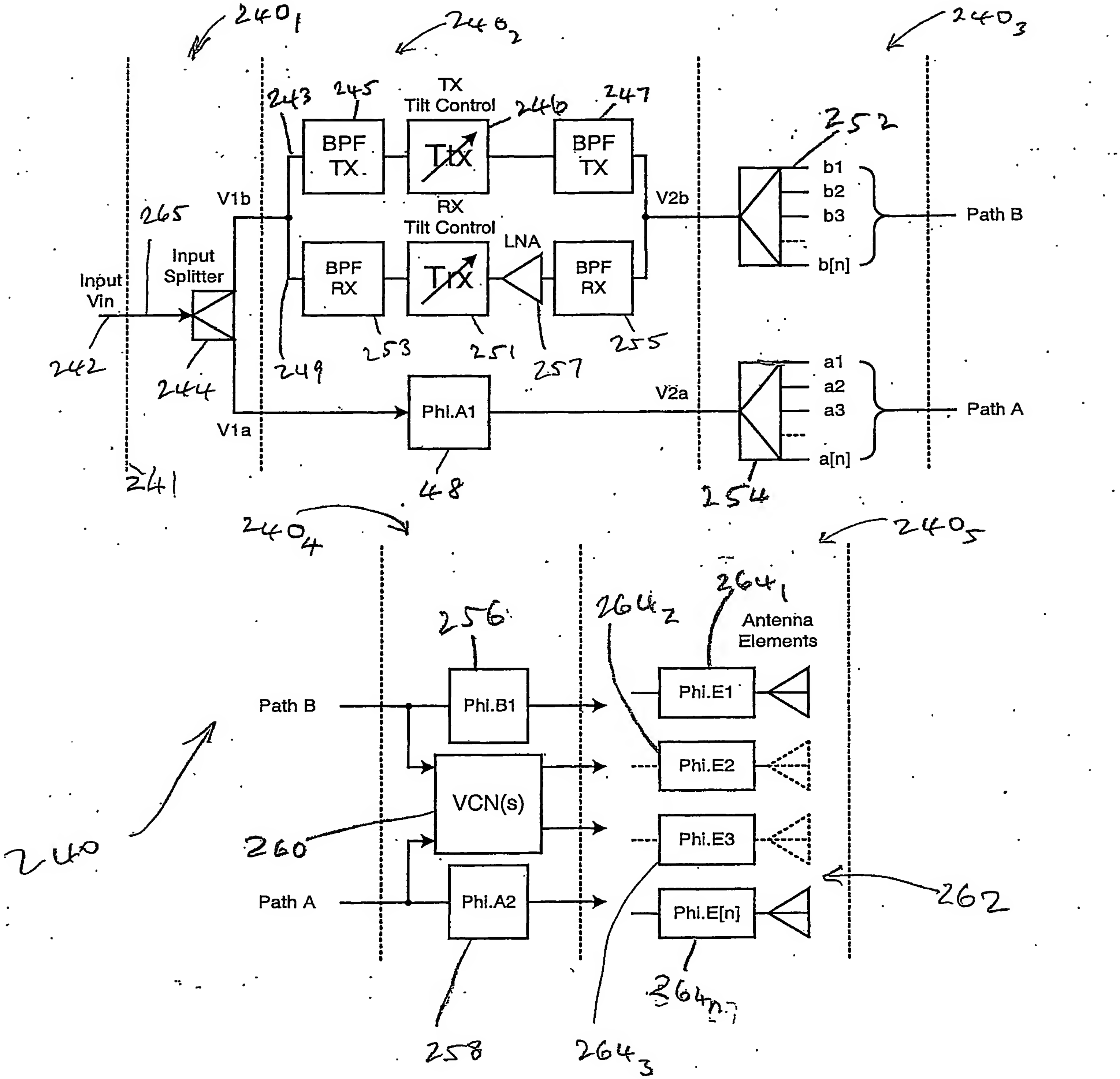
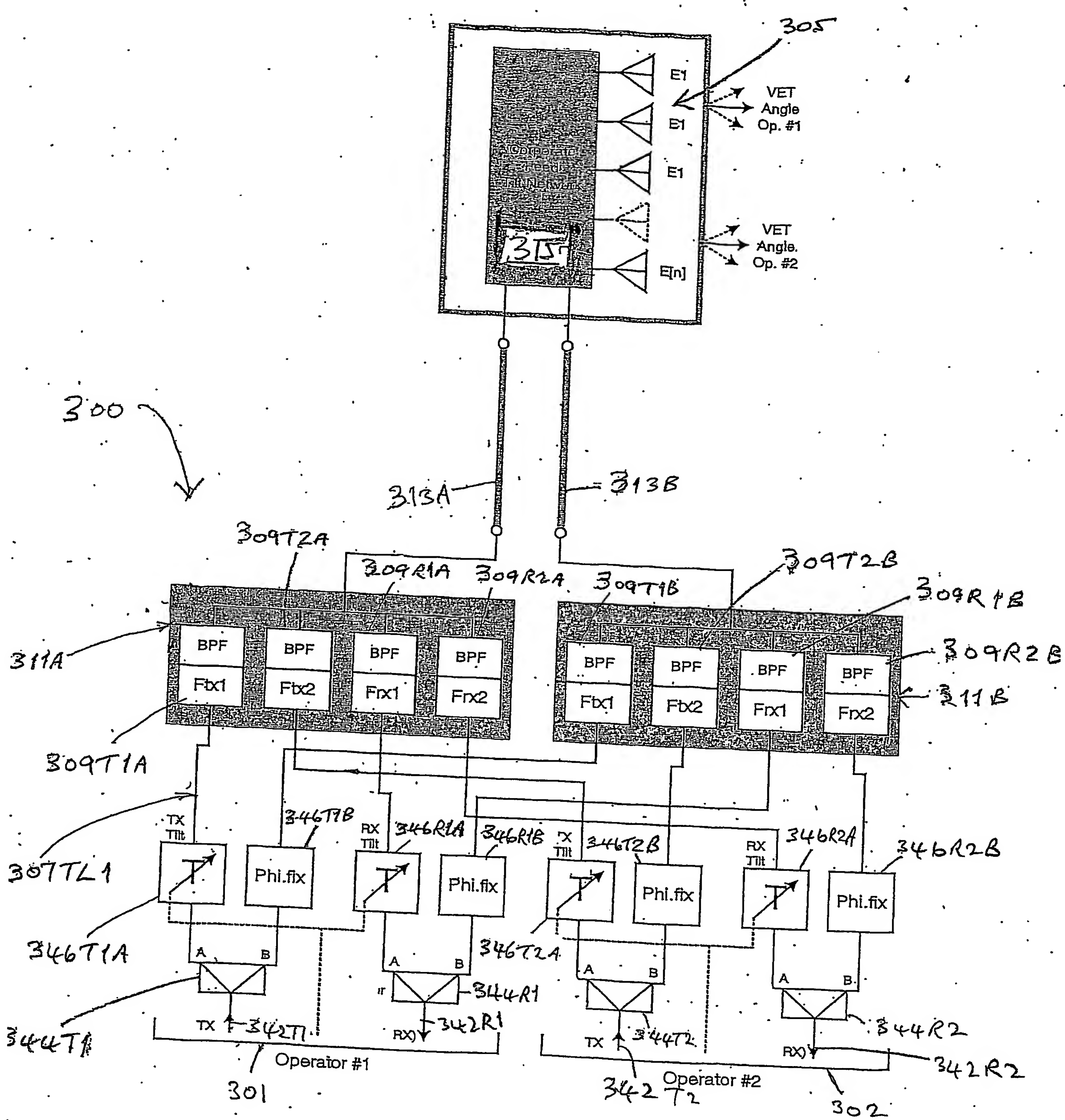


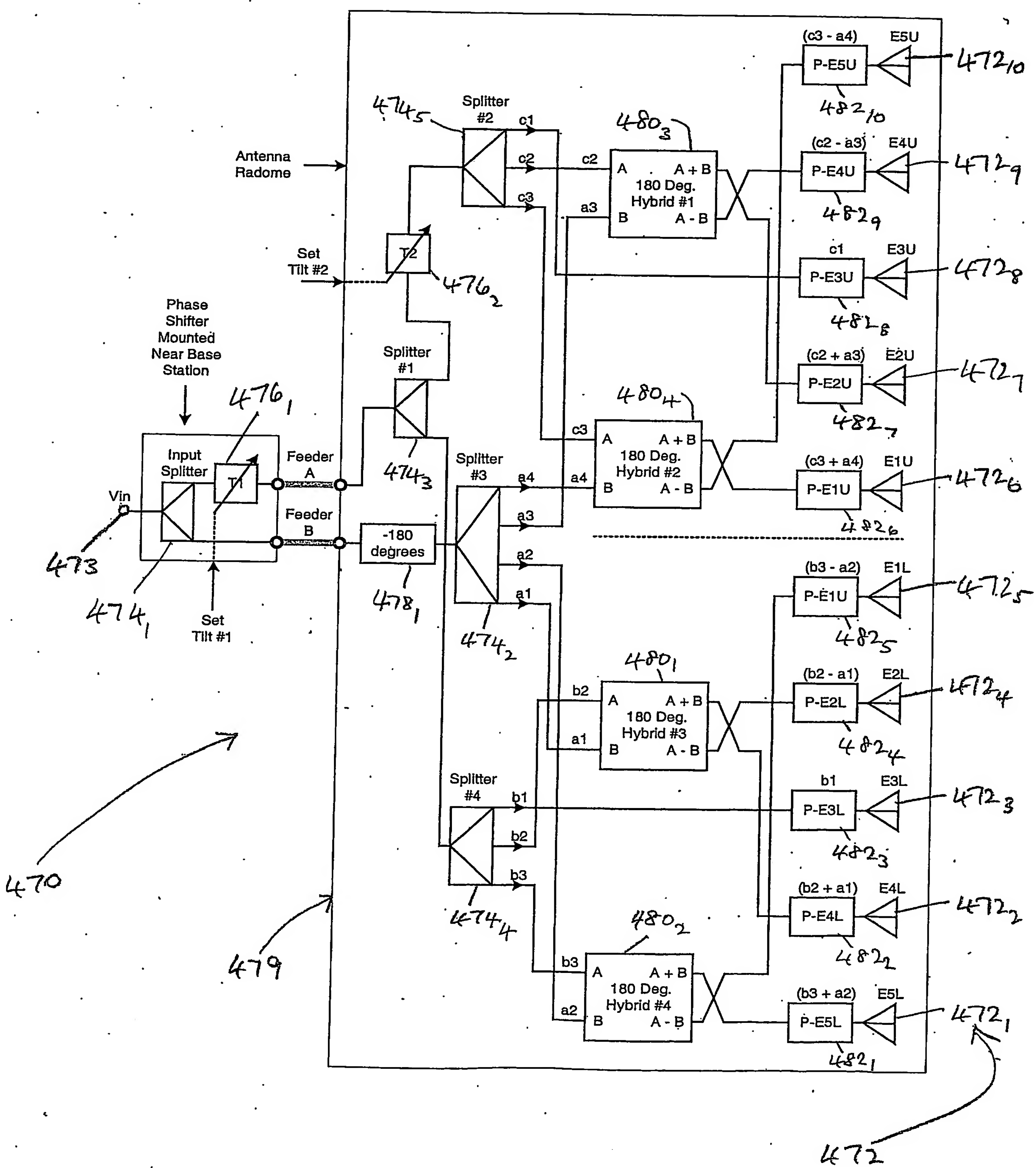
FIGURE 13



240_1
240_2
240_3
Input Vin
Input Splitter
V1b
V1a
243
245
TX Tilt Control
246
247
BPF TX
Ttx
BPF TX
RX Tilt Control
LNA
BPF RX
Trx
BPF RX
V2b
V2a
252
b1
b2
b3
b[n]
Path B
a1
a2
a3
a[n]
Path A
Phi.A1
265
242
244
249
253
251
257
255
241
48
254
240_4
240_5
256
264_2
264_1
Antenna Elements
Path B
Phi.B1
VCN(s)
Phi.A2
Path A
Phi.E1
Phi.E2
Phi.E3
Phi.E[n]
260
240
262
264_n
258
264_3

FIGURE 14


305
E1
E1
E1
E[n]
VET
Angle
Op. #1
VET
Angle.
Op. #2
315
300
313A
313B
309T2A
309R1A
309R2A
309T1B
309T2B
309R1B
309R2B
311A
311B
BPF
Ftx1
Ftx2
Frx1
Frx2
309T1A
307TL1
TX
Tilt
RX
Tilt
346T1B
346R1A
346R1B
346T2B
346R2A
346R2B
Phi.fix
346T1A
346T2A
A
B
344R1
344T1
TX
342T1
RX
342R1
344T2
344R2
Operator #1
Operator #2
301
342 T2
302
342R2


Antenna
Radome
Splitter
#2
c1
c2
c3
Set
Tilt #2
T2
Phase
Shifter
Mounted
Near Base
Station
Splitter
#1
Input
Splitter
T1
Feeder
A
Feeder
B
Vin
-180
degrees
Set
Tilt #1
Splitter
#3
a4
a3
a2
a1
Splitter
#4
b1
b2
b3
A
A + B
180 Deg.
Hybrid #1
B
A - B
180 Deg.
Hybrid #2
180 Deg.
Hybrid #3
180 Deg.
Hybrid #4
(c3 - a4)
E5U
P-E5U
(c2 - a3)
E4U
P-E4U
c1
E3U
P-E3U
(c2 + a3)
E2U
P-E2U
(c3 + a4)
E1U
P-E1U
(b3 - a2)
E1L
P-E1U
(b2 - a1)
E2L
P-E2L
b1
E3L
P-E3L
(b2 + a1)
E4L
P-E4L
(b3 + a2)
E5L
P-E5L
470
472
473
479
474_1
474_2
474_3
474_4
474_5
476_1
476_2
478_1
480_1
480_2
480_3
480_4
472_1
472_2
472_3
472_4
472_5
472_6
472_7
472_8
472_9
472_{10}
482_1
482_2
482_3
482_4
482_5
482_6
482_7
482_8
482_9
482_{10}

PCT/GB2004/002016